The Universe According to Planck

Lloyd Knox

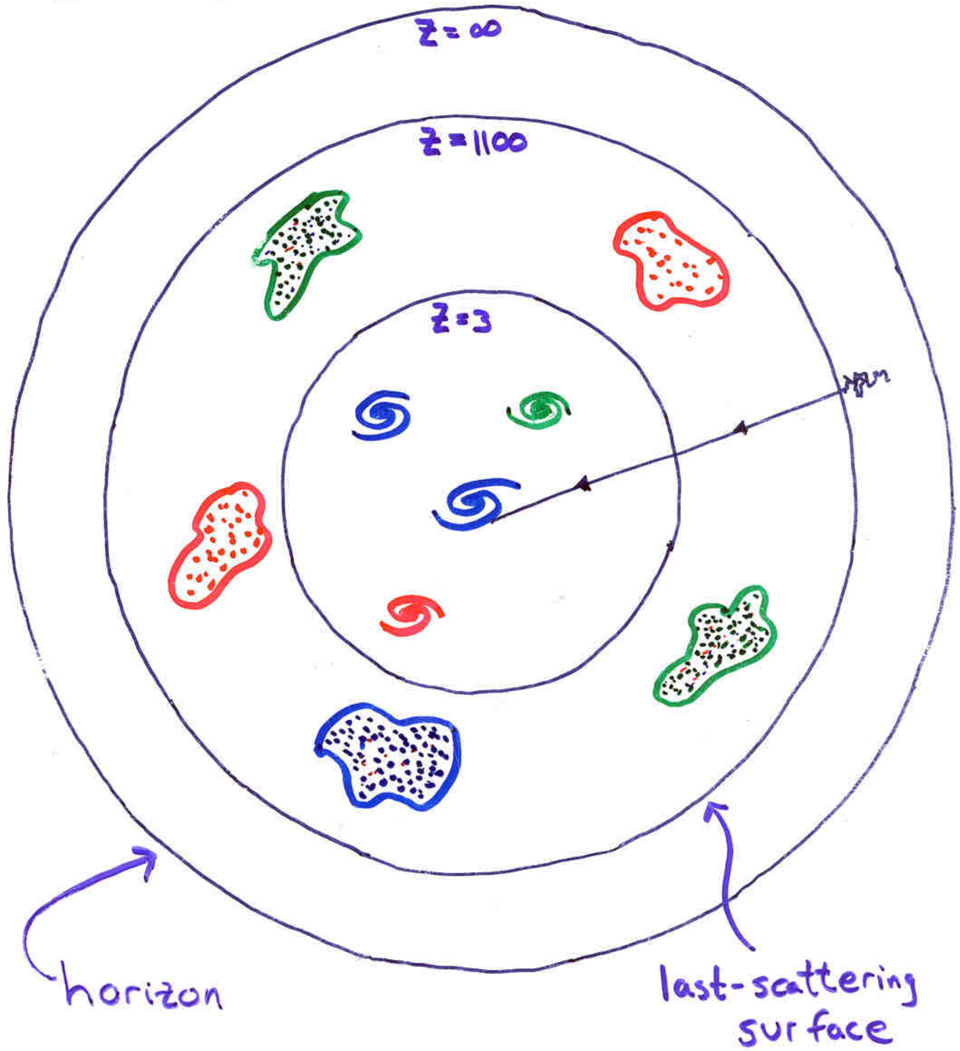
UC Davis

Planck Collaboration

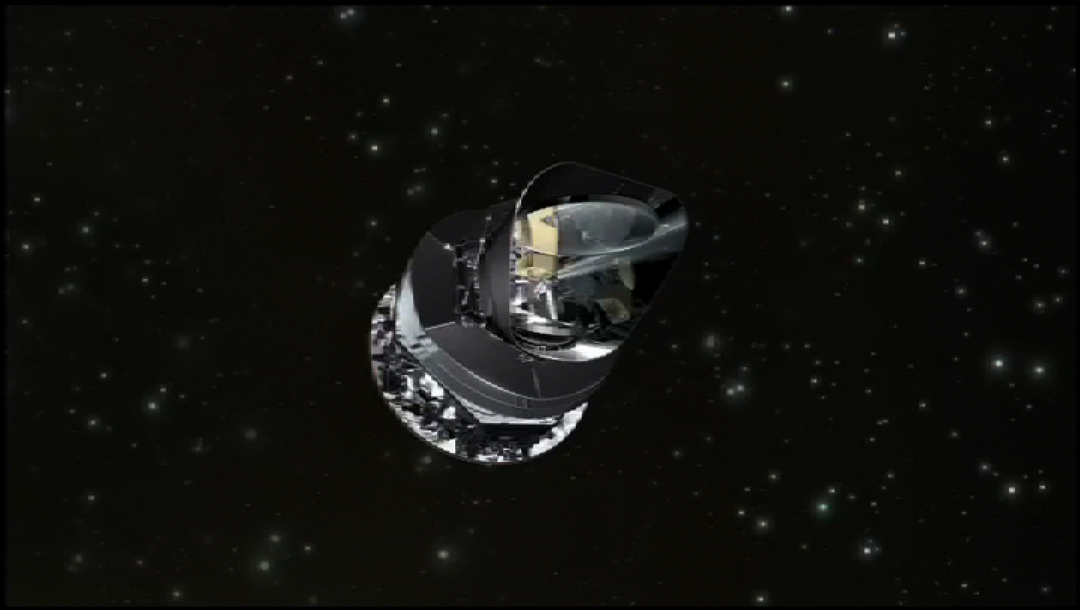
Gravity has driven the Universe from simple/linear to complex/non-linear.

It has proven very profitable to study it when it was in the simple/linear regime where, given a model, we can make highly precise predictions.

THE HISTORY OF A SINGLE PHOTON



A Journey of Light



through Space and Time

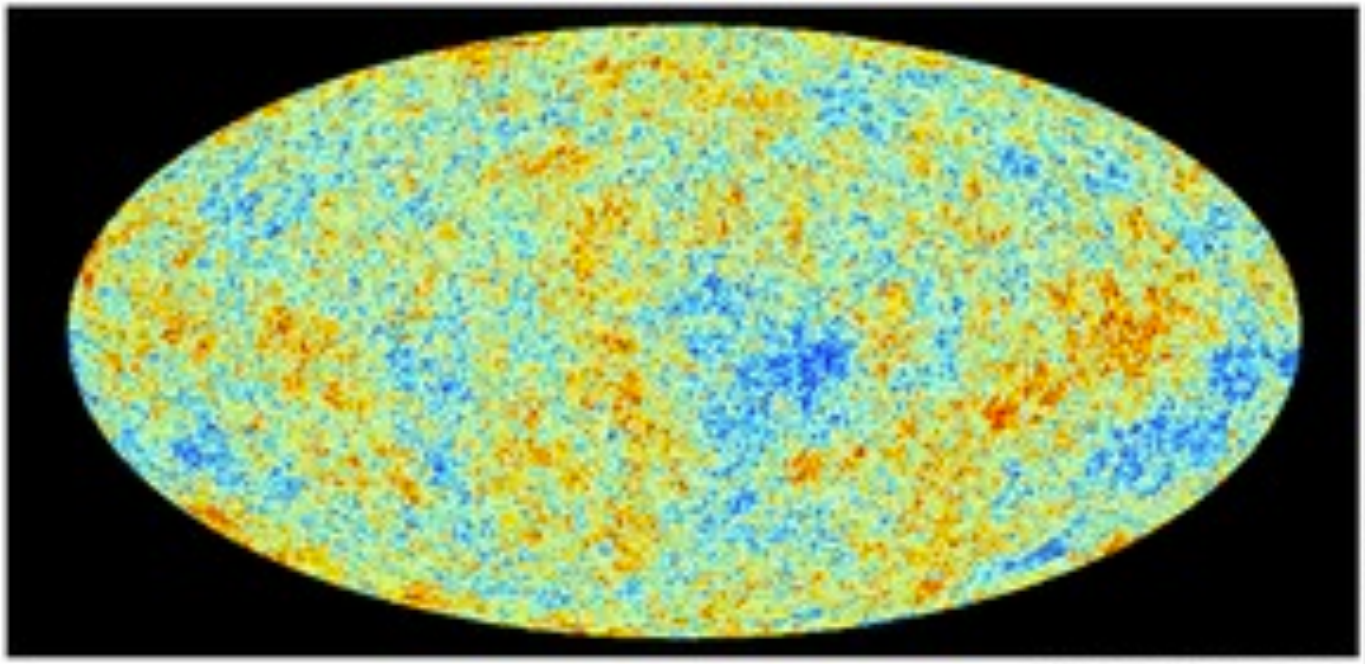
"All the News
That's Fit to Print"

The New York Times

Late Edition

NEW YORK, FRIDAY, MARCH 22, 2013

$2.50



The Cosmos, Back in the Day

PRESIDENT URGES ISRAELIS TO PUSH EFFORT FOR PEACE

APPEAL AIMED AT YOUNG

In Jerusalem, He Eases Stance on Settlement Halt Before Talks

Outline

- Planck
- ΛCDM, the standard model of cosmology, passes a precision test
- Consistency with Other Cosmological Probes
- Gravitational Lensing of the CMB
- Implications for
  - Neutrinos
  - Big Bang Nucleosynthesis
  - Inflation

Outline

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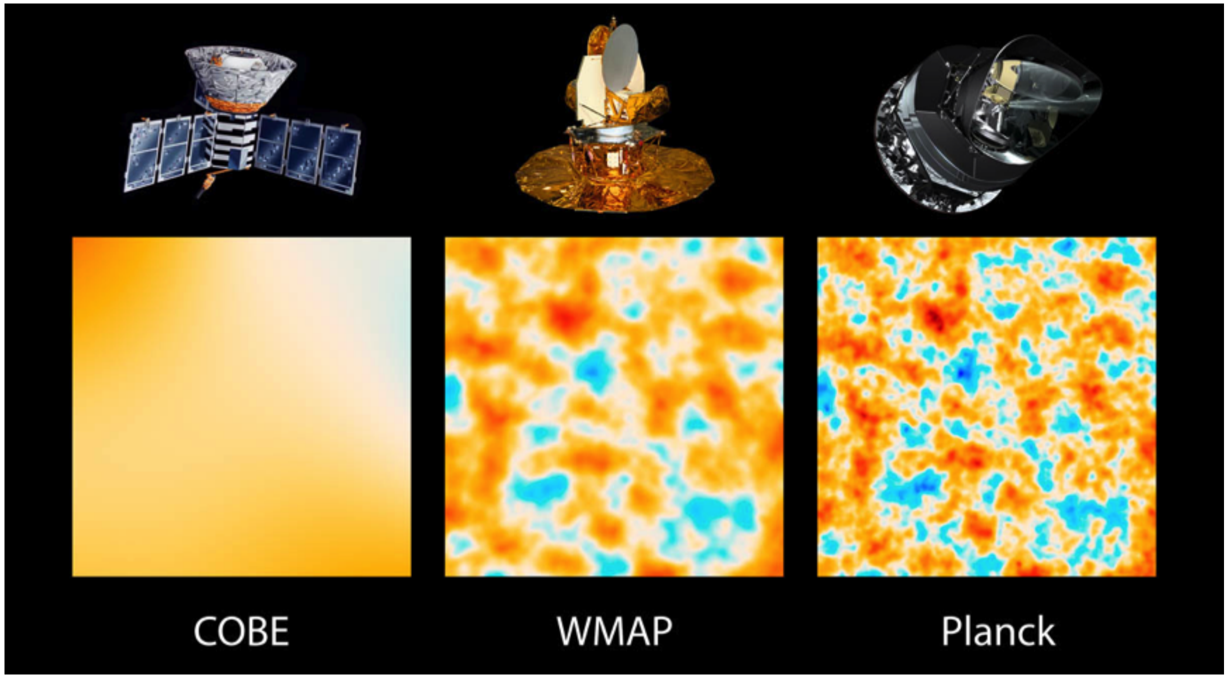
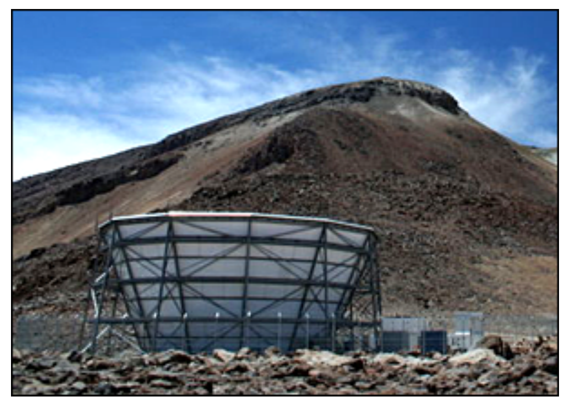
What is Planck?

Full sky:



Better resolution:

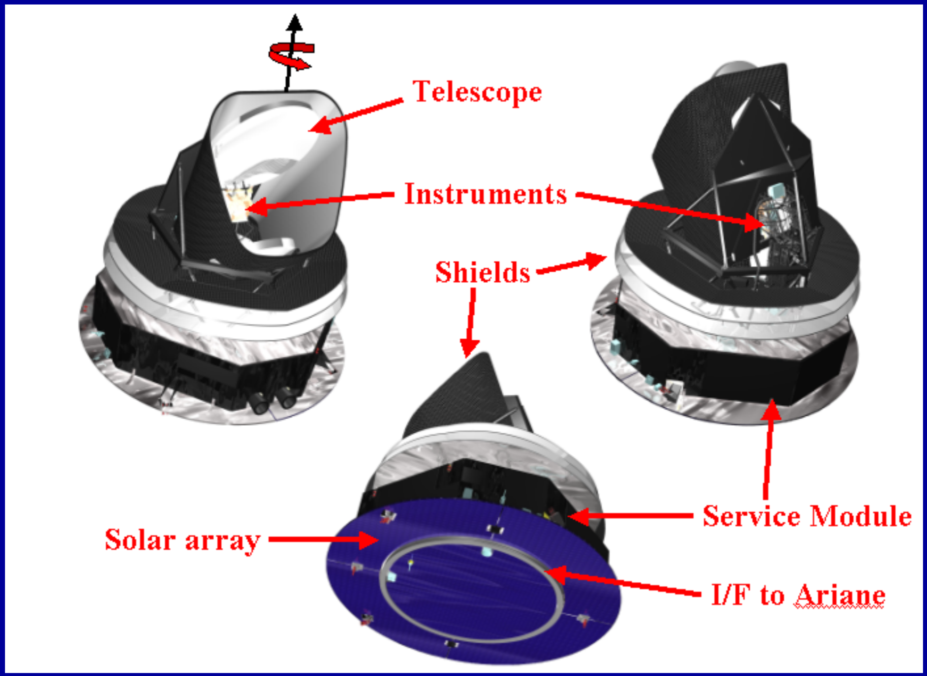
South Pole Telescope (SPT)

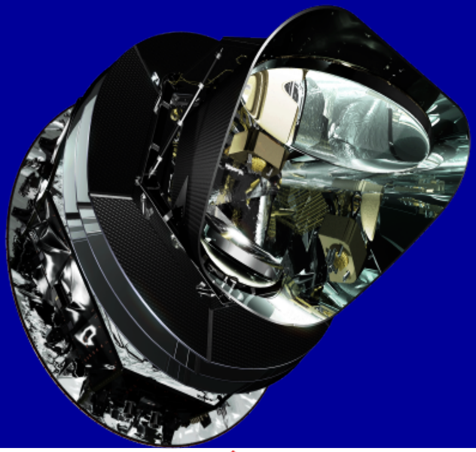


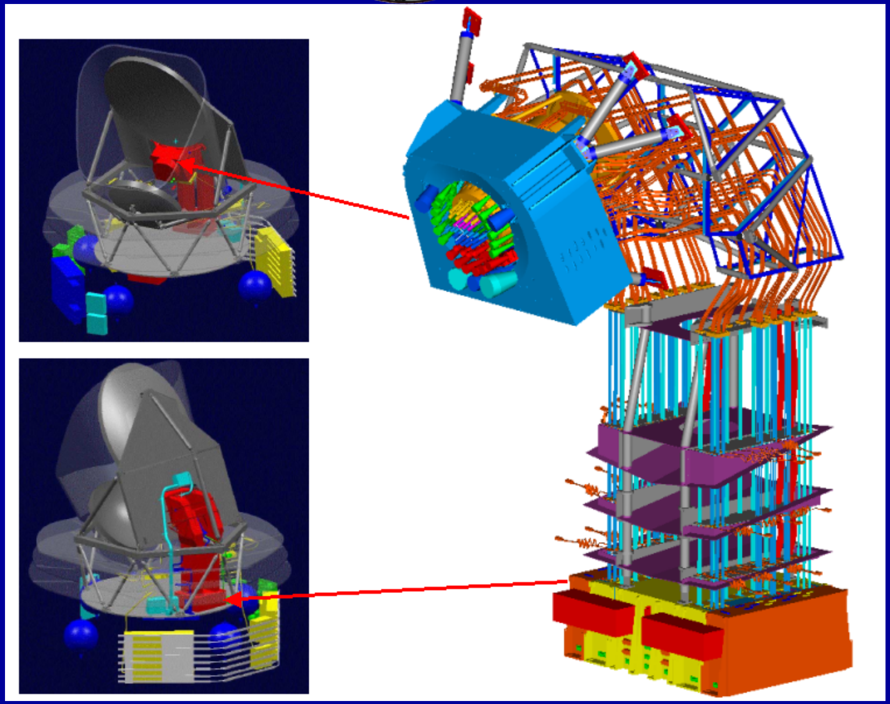
Atacama Cosmology Telescope (ACT)

Planck in February 2009

Planck in cartoons



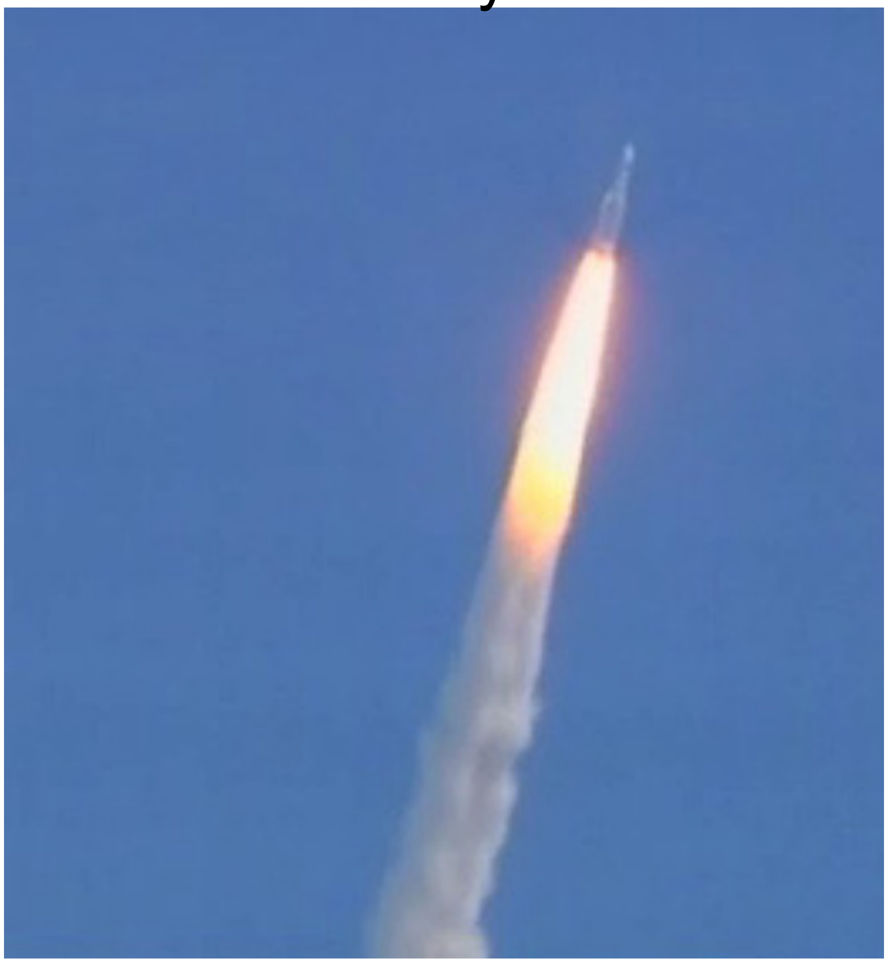


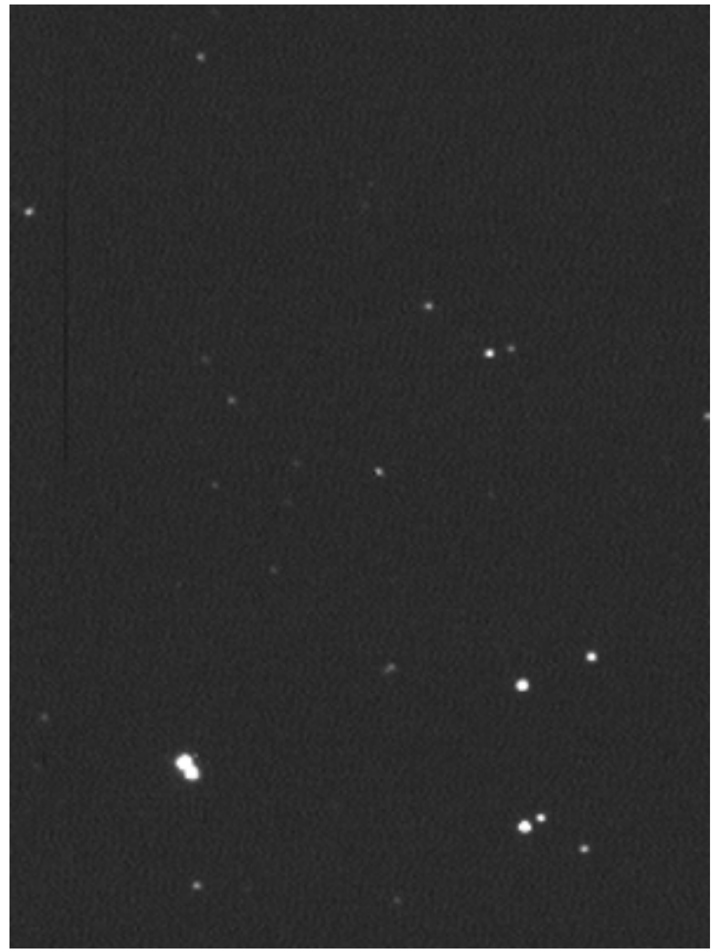


Planck has two instruments, the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI) in a shared focal plane containing 74 channels and covering 8 degrees on the sky.

A picture-perfect launch!

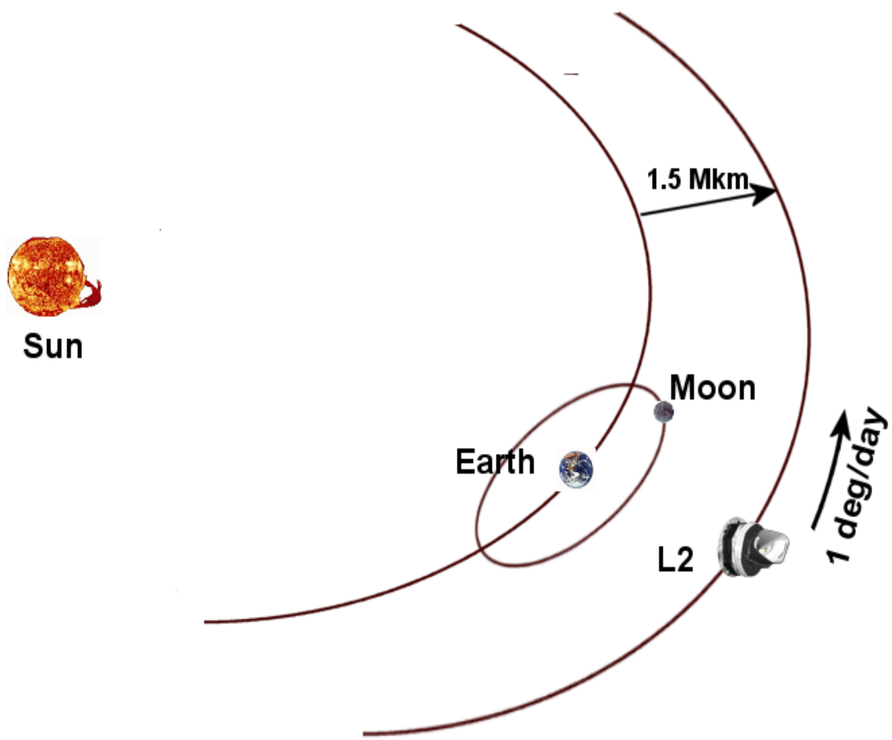
Ariane 5 lifts off with Herschel and Planck on board on 14 May 2009 at 15:12:02 CEST.

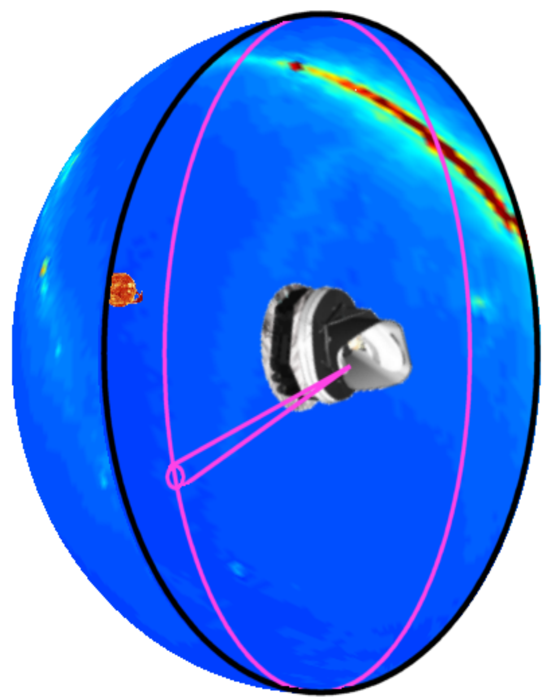




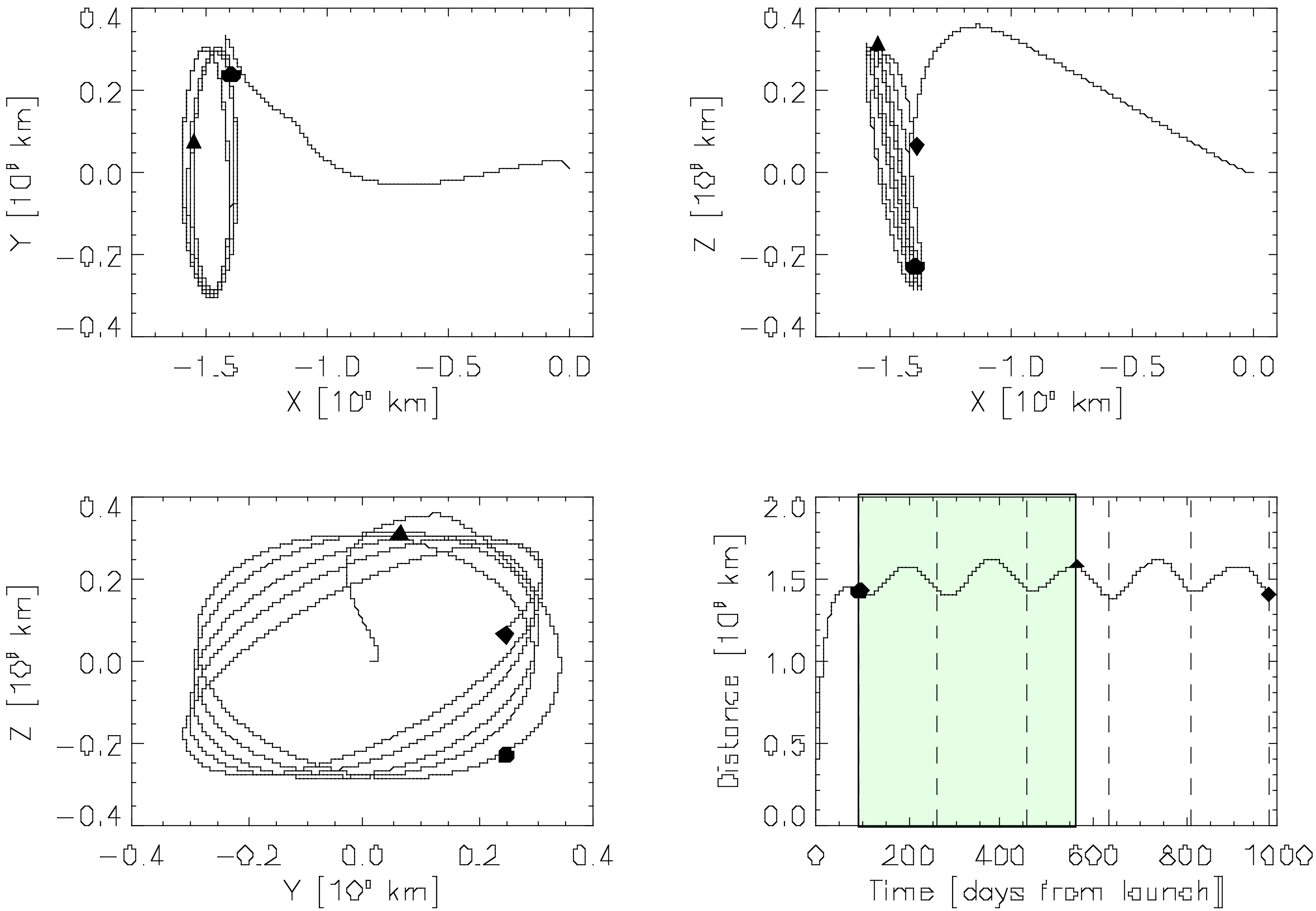
The orbit

Planck makes a map of the full sky every ~6 months.





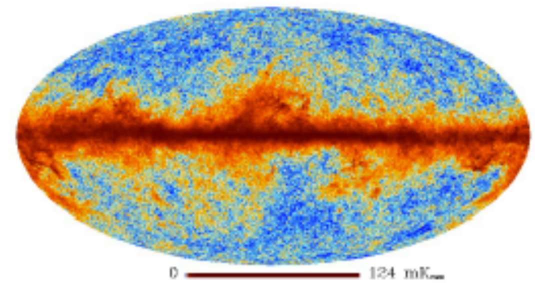
Orbit

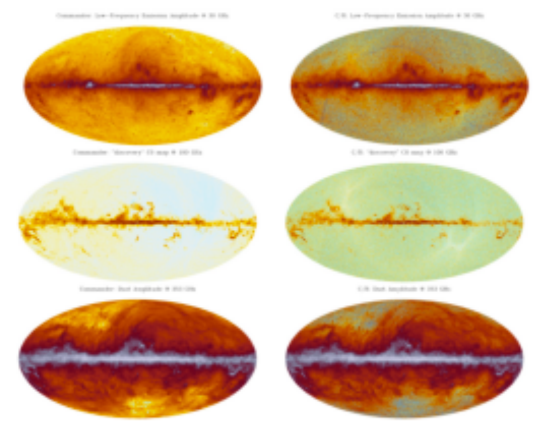


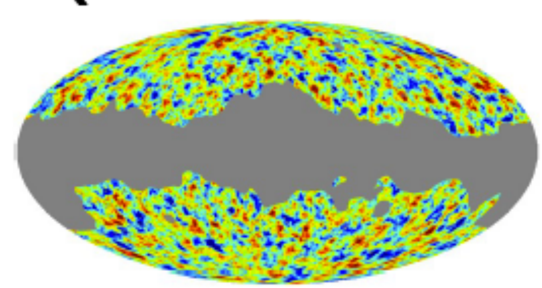
Y [10^6 km]
X [10^6 km]
Z [10^6 km]
X [10^6 km]
Z [10^6 km]
Y [10^6 km]
Distance [10^6 km]
Time [days from launch]

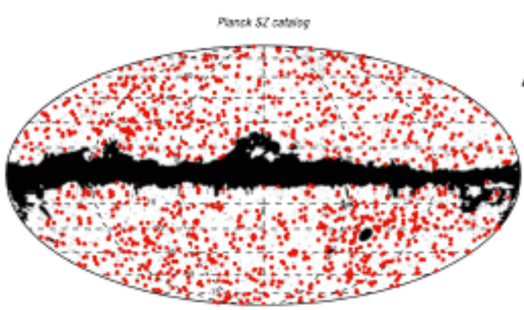
What has been released ~~today~~? 3/21/13

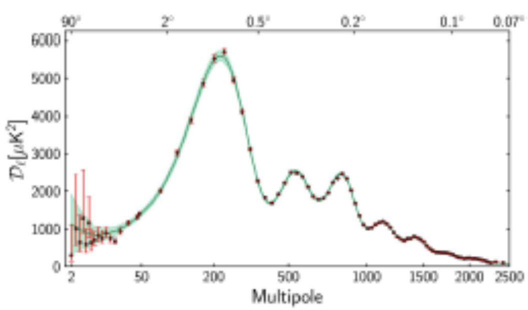
- Products
  - Detector maps
  - Component separated maps
  - Lensing reconstruction maps
  - TT, ΦΦ power spectrum
  - Likelihood software
  - SZ cluster catalog

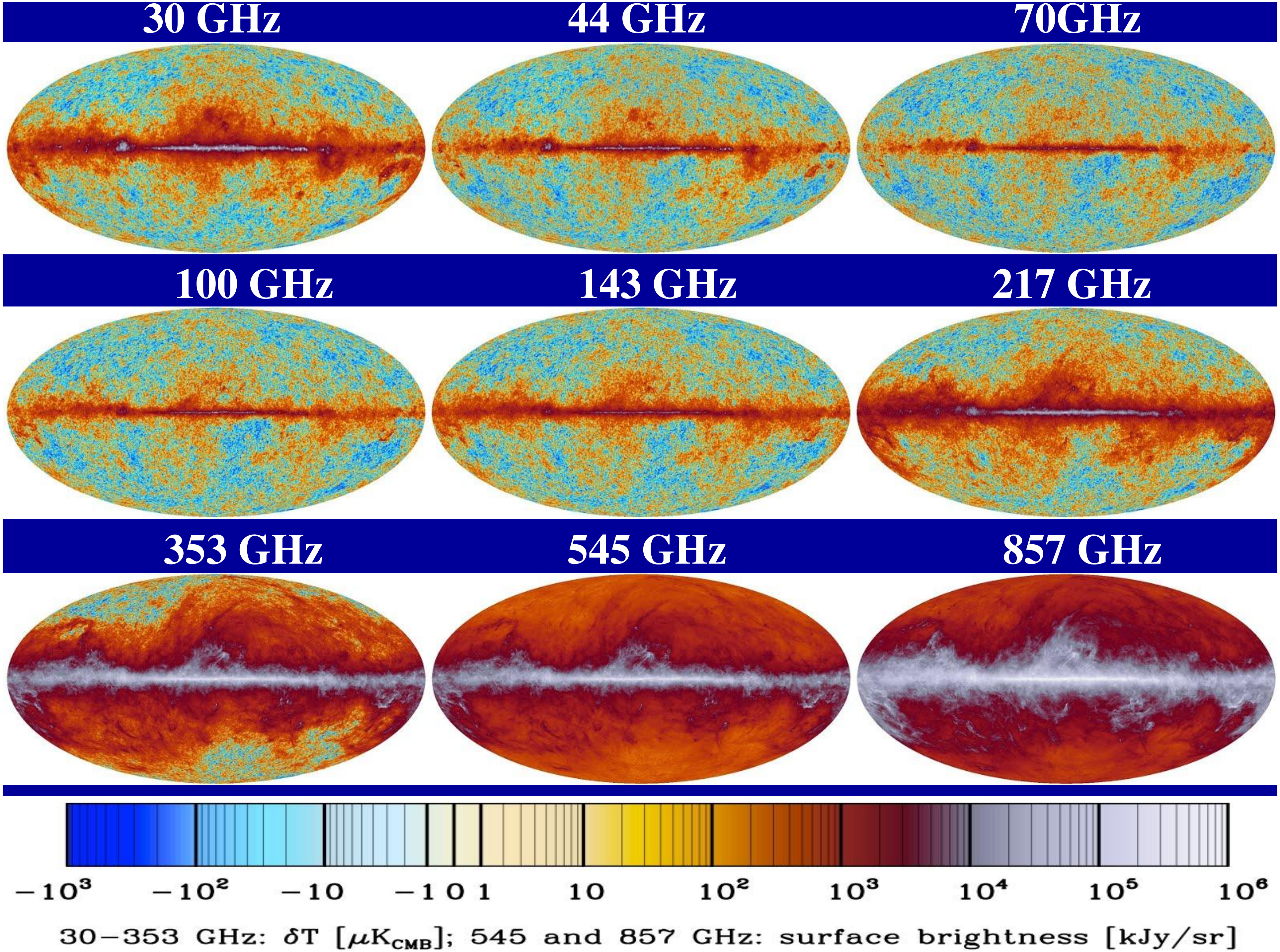




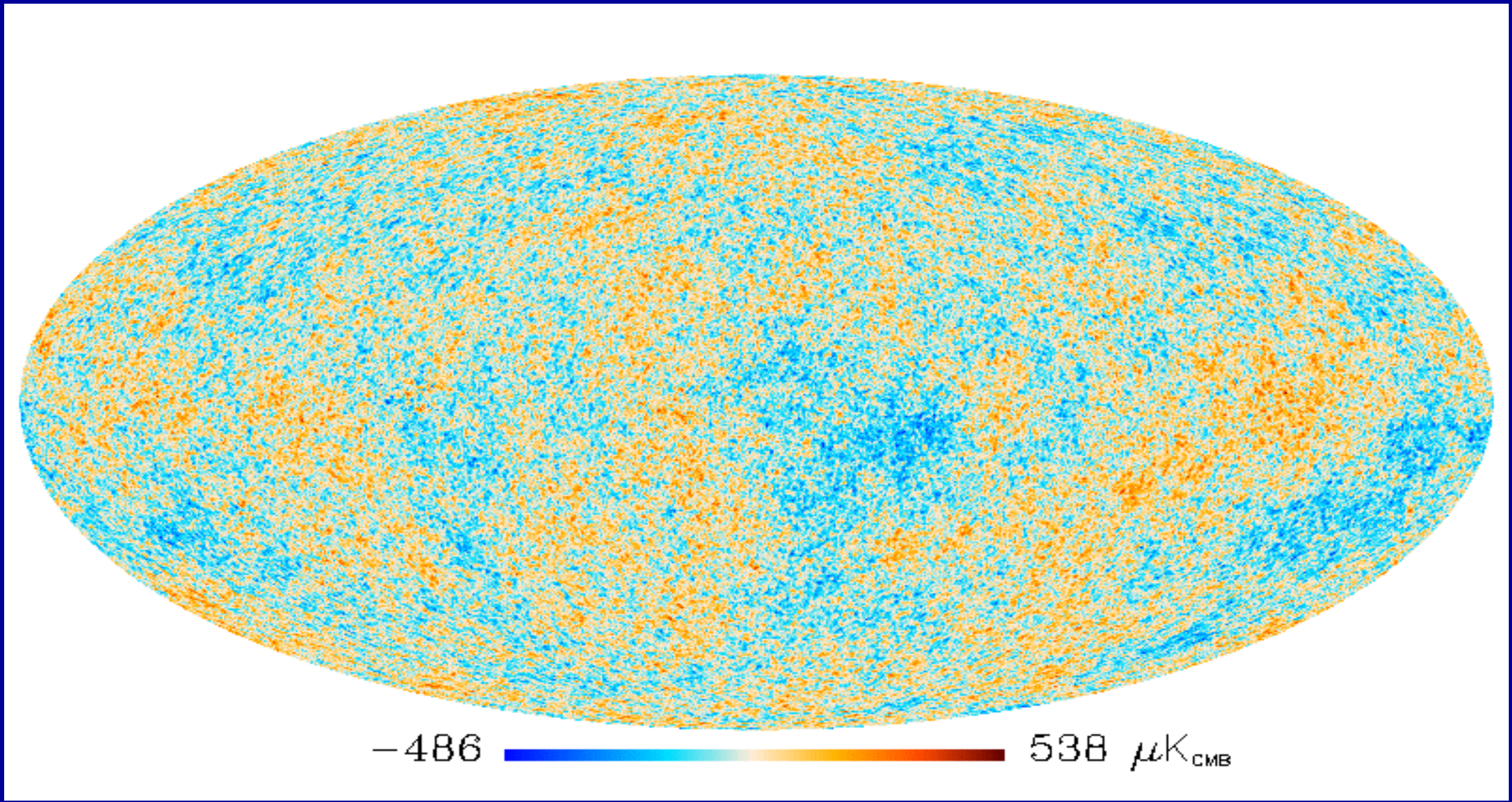







30 GHz
44 GHz
70GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

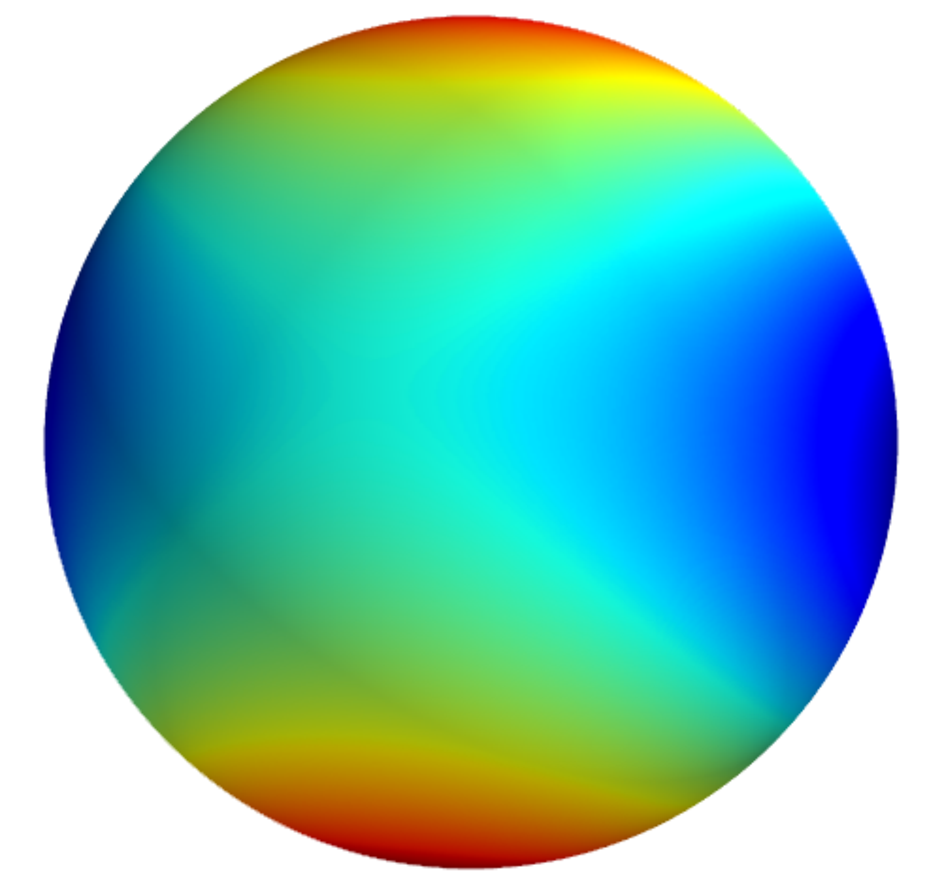
Foreground cleaned CMB map



$\Delta\, T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$

l = oscillations per 360 degrees

A quadrupole mode (l=2)

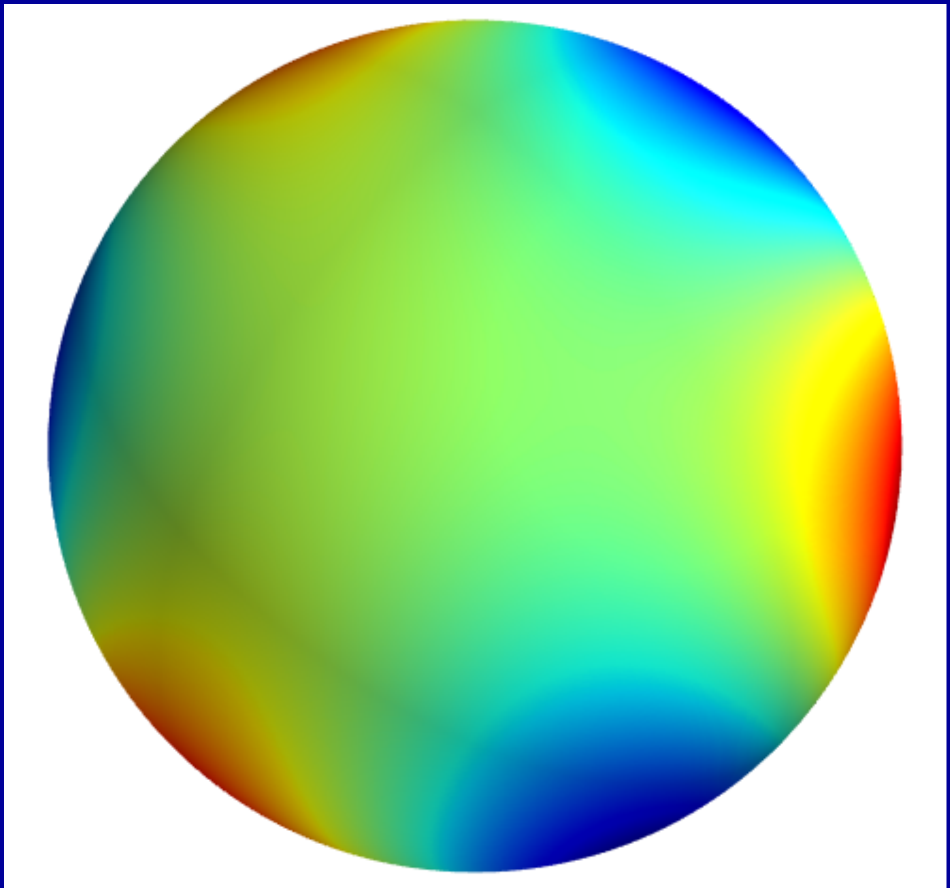


Y_{20}

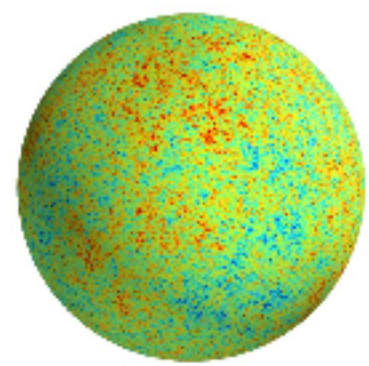
$\Delta T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$

l = oscillations per 360 degrees

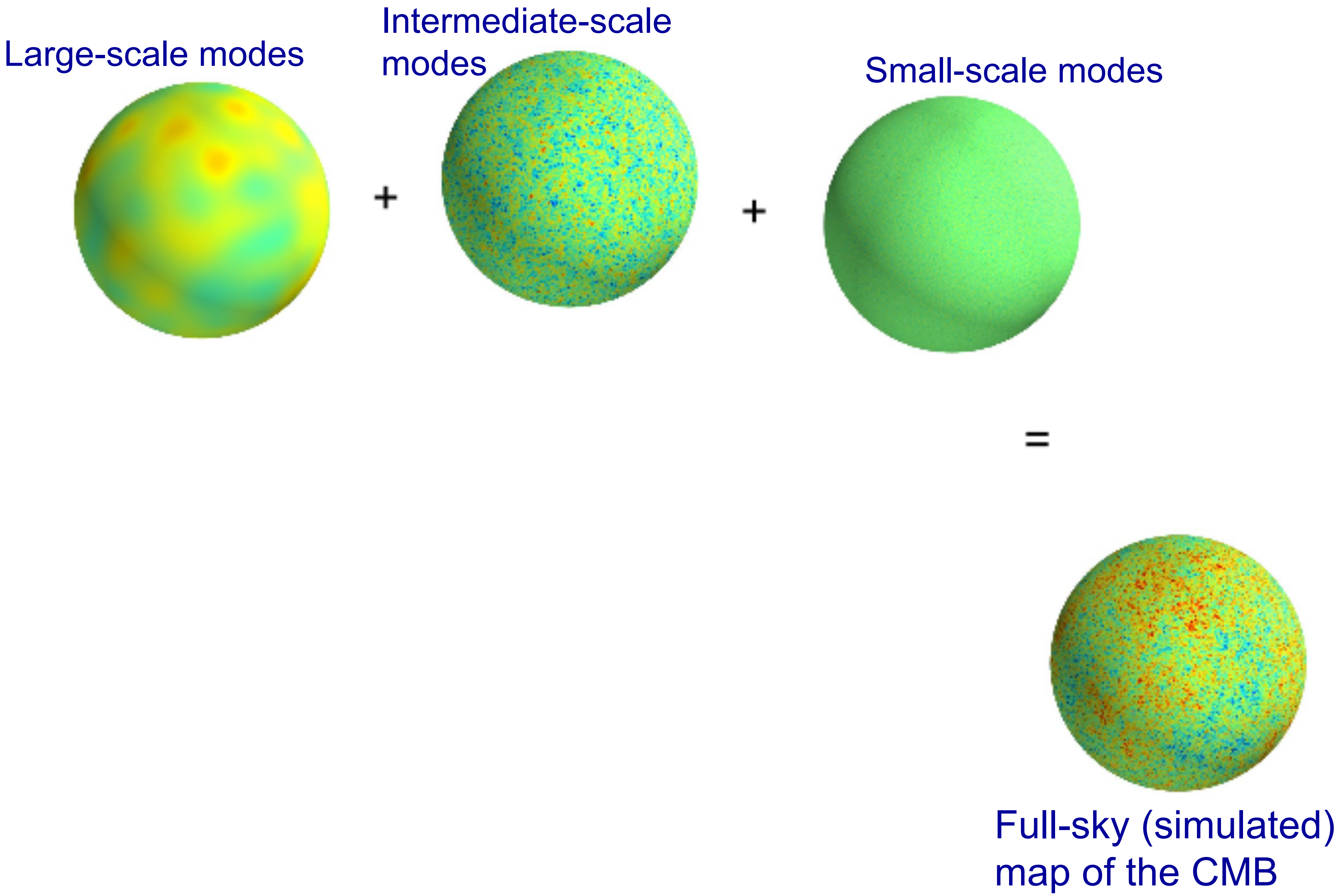
An octupole mode (l=3)



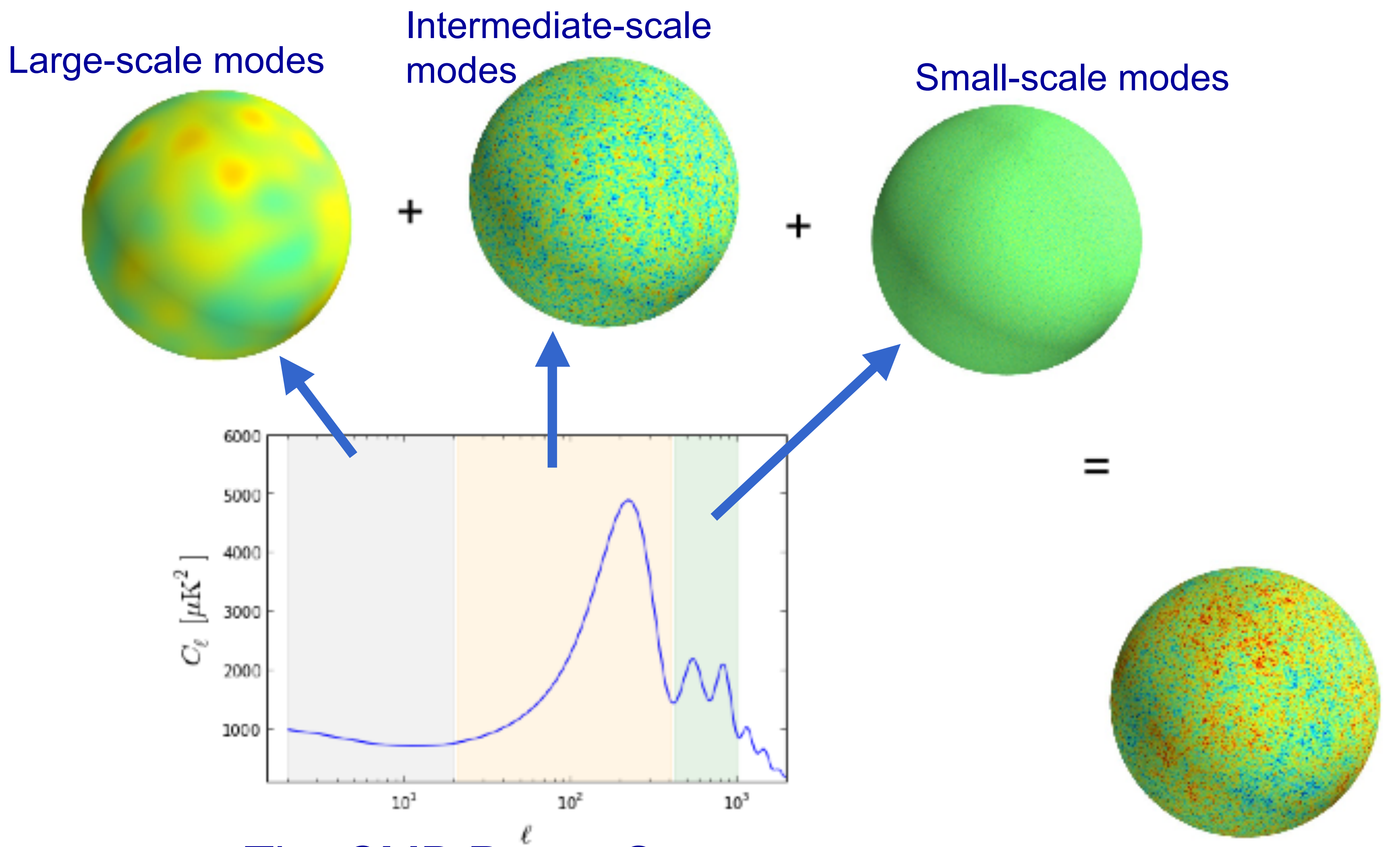
Y_{30}



Full-sky (simulated)
map of the CMB


Large-scale modes
Intermediate-scale modes
Small-scale modes
+
+
=
Full-sky (simulated) map of the CMB

$C_l = \langle |a_{lm}|^2 \rangle$



The CMB Power Spectrum

l = oscillations per 360 degrees

Full-sky (simulated) map of the CMB

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- ΛCDM, the standard model of cosmology, passes a precision test
- Consistency with Other Cosmological Probes
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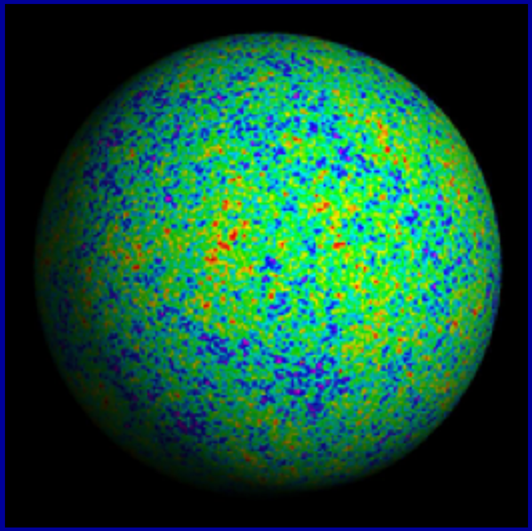
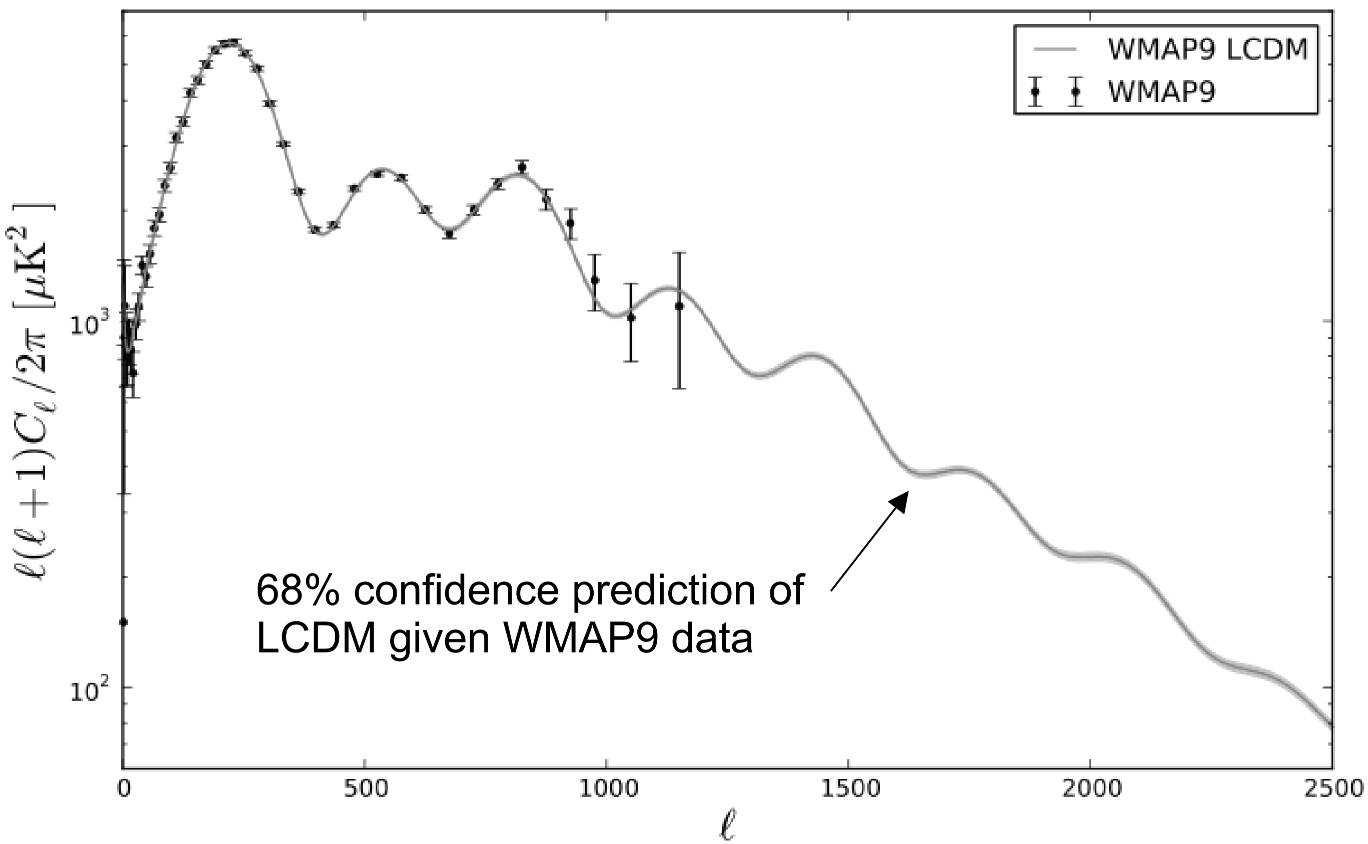
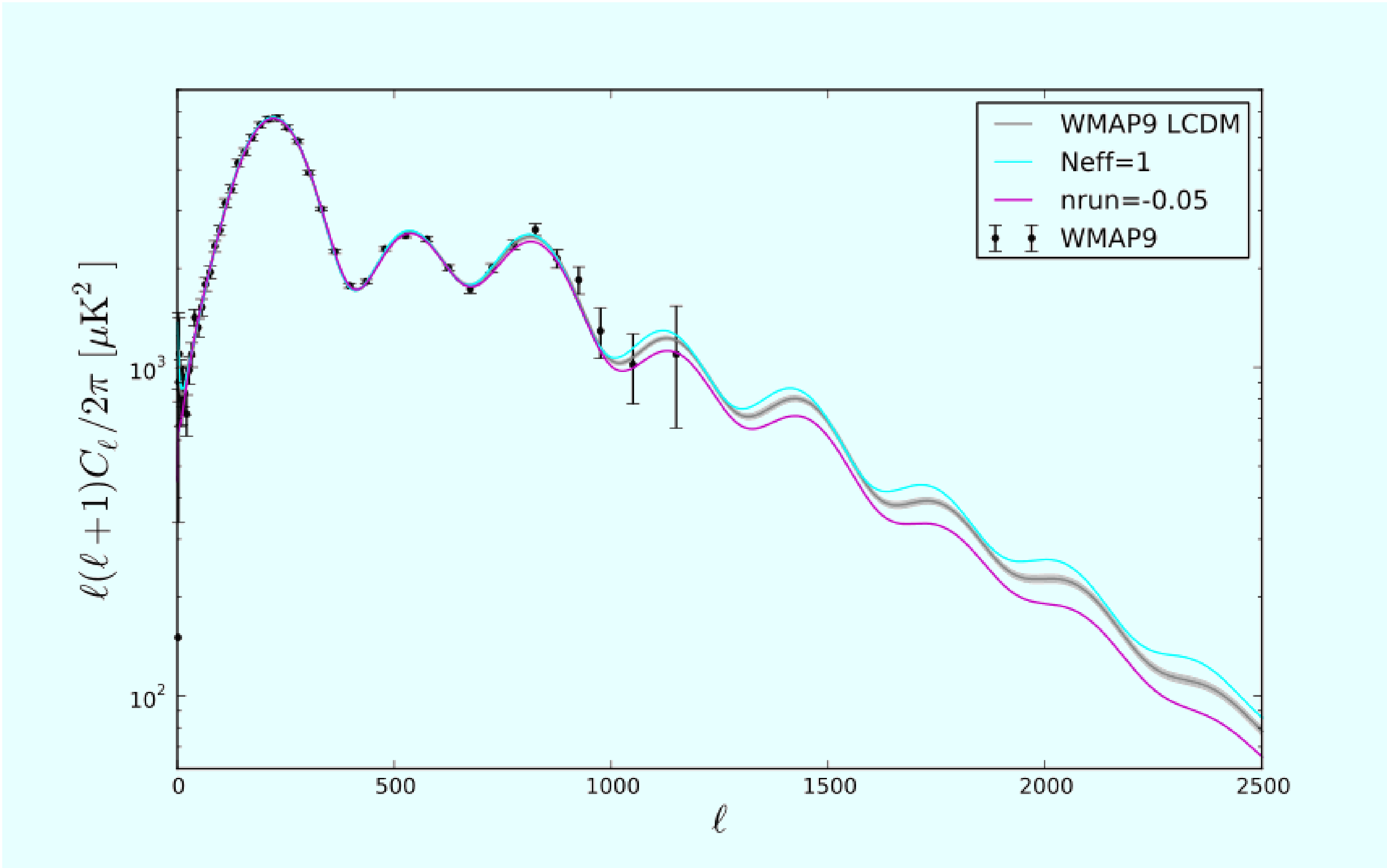
The 6-parameter Standard Model of Cosmology: ΛCDM



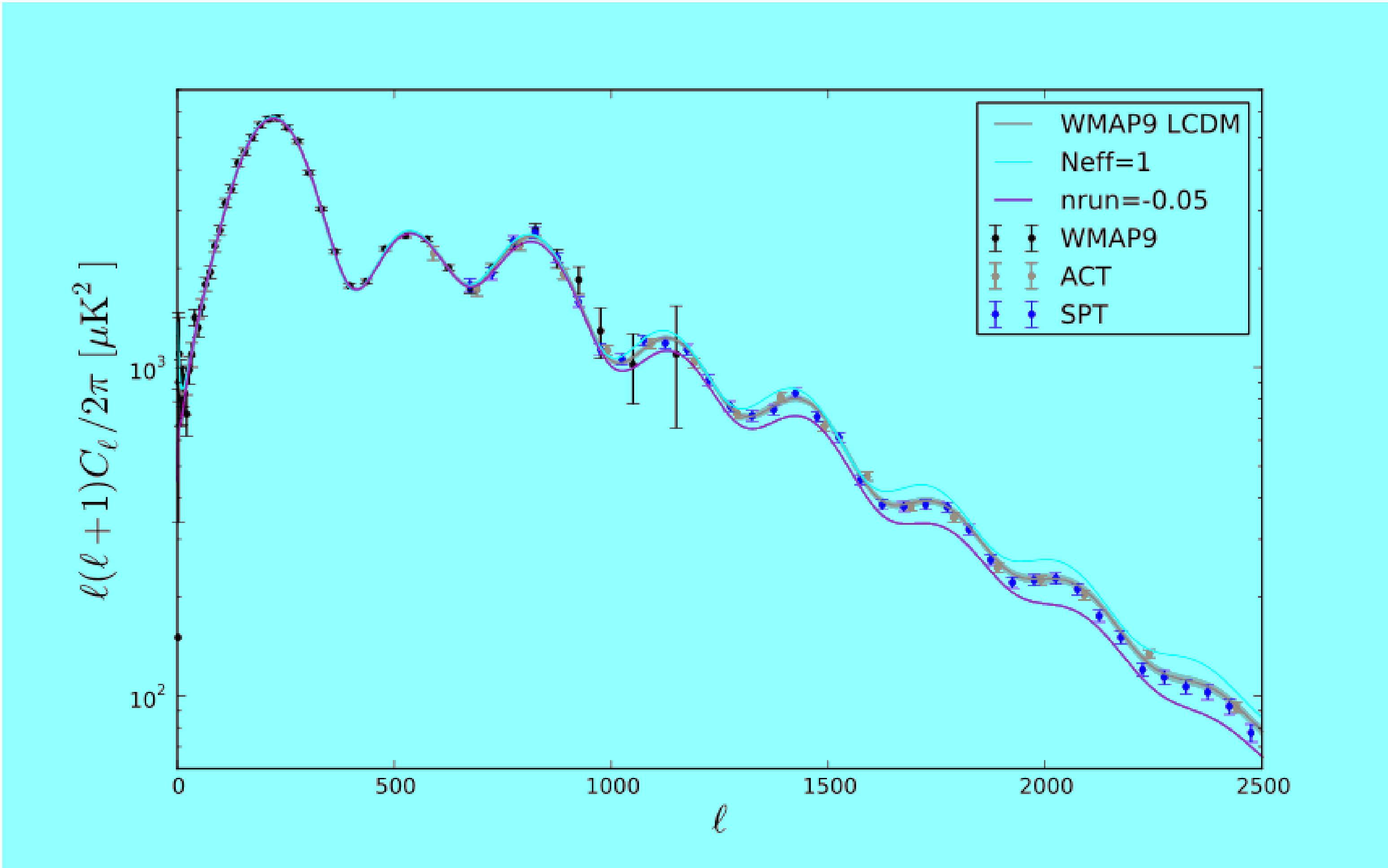
- Matter content:
  - nuclei, electrons, 3 ν species, photons
  - BBN Consistent amount of Helium
  - Cold Dark matter
  - Dark energy is a cosmological constant
- Space-time (at early times)
  - (Nearly) Homogeneous and isotropic
  - Gaussian adiabatic perturbations with a nearly scale-invariant spectrum well described by a power law
- Extensions
  - More/less than 3 neutrinos, free neutrino mass, free Helium, non-zero mean curvature, quintessence, running of the spectral index, non-Gaussianity...

LCDM makes a very precise prediction

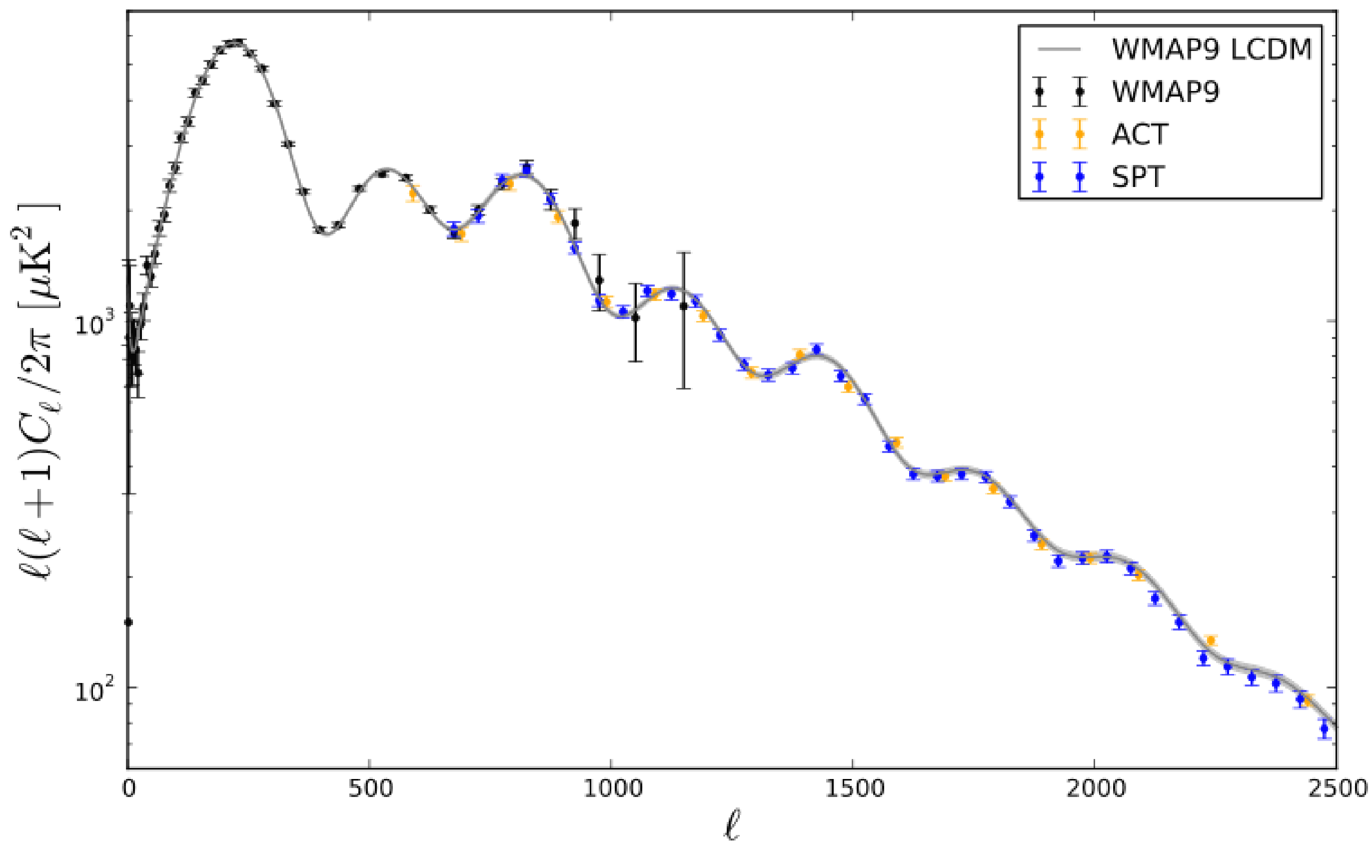




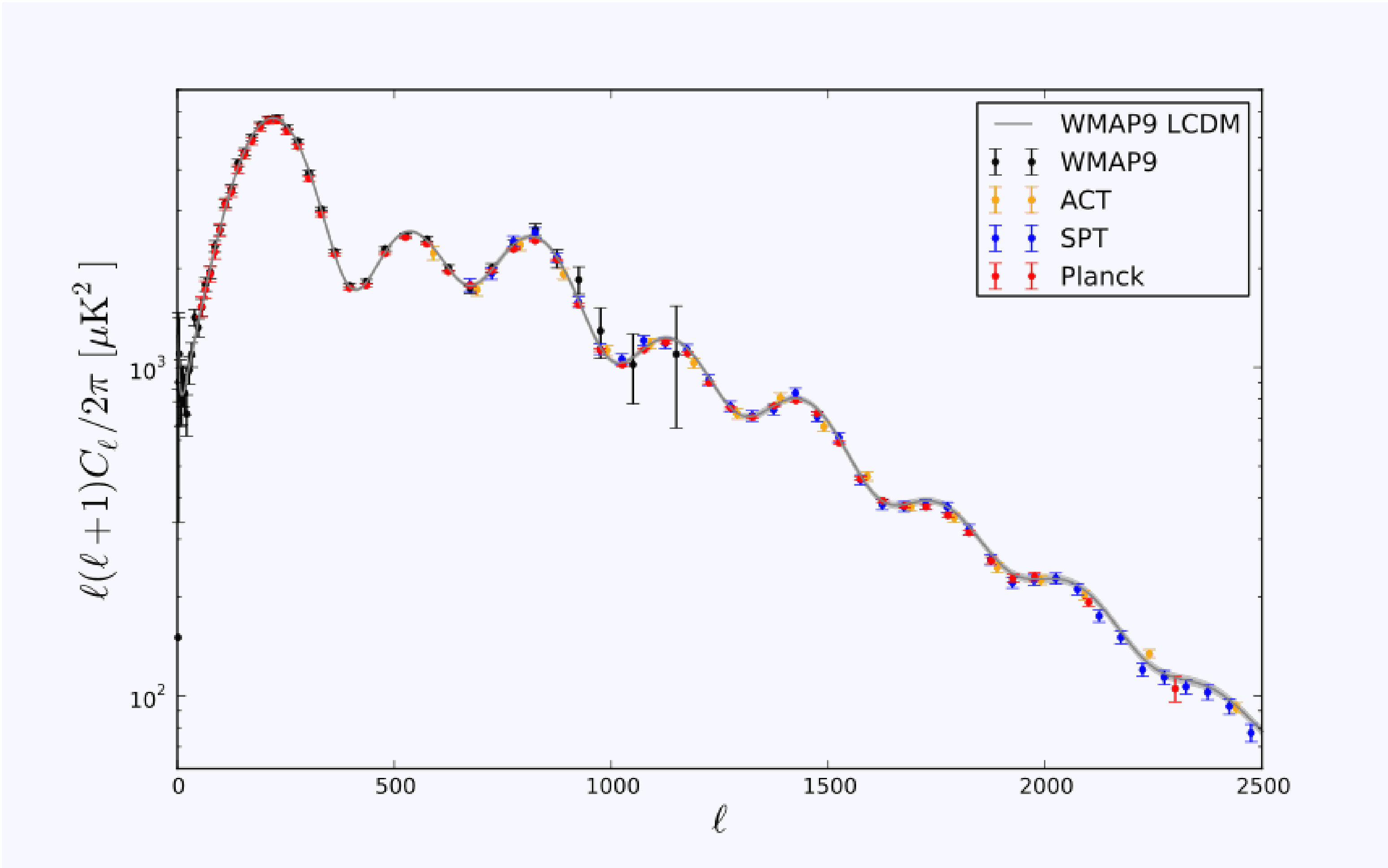
WMAP9 LCDM
Neff=1
nrun=-0.05
WMAP9
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ



WMAP9 LCDM
Neff=1
nrun=-0.05
WMAP9
ACT
SPT
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ



WMAP9 LCDM
WMAP9
ACT
SPT
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ


WMAP9 LCDM
WMAP9
ACT
SPT
Planck
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^3
10^2
0
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2000
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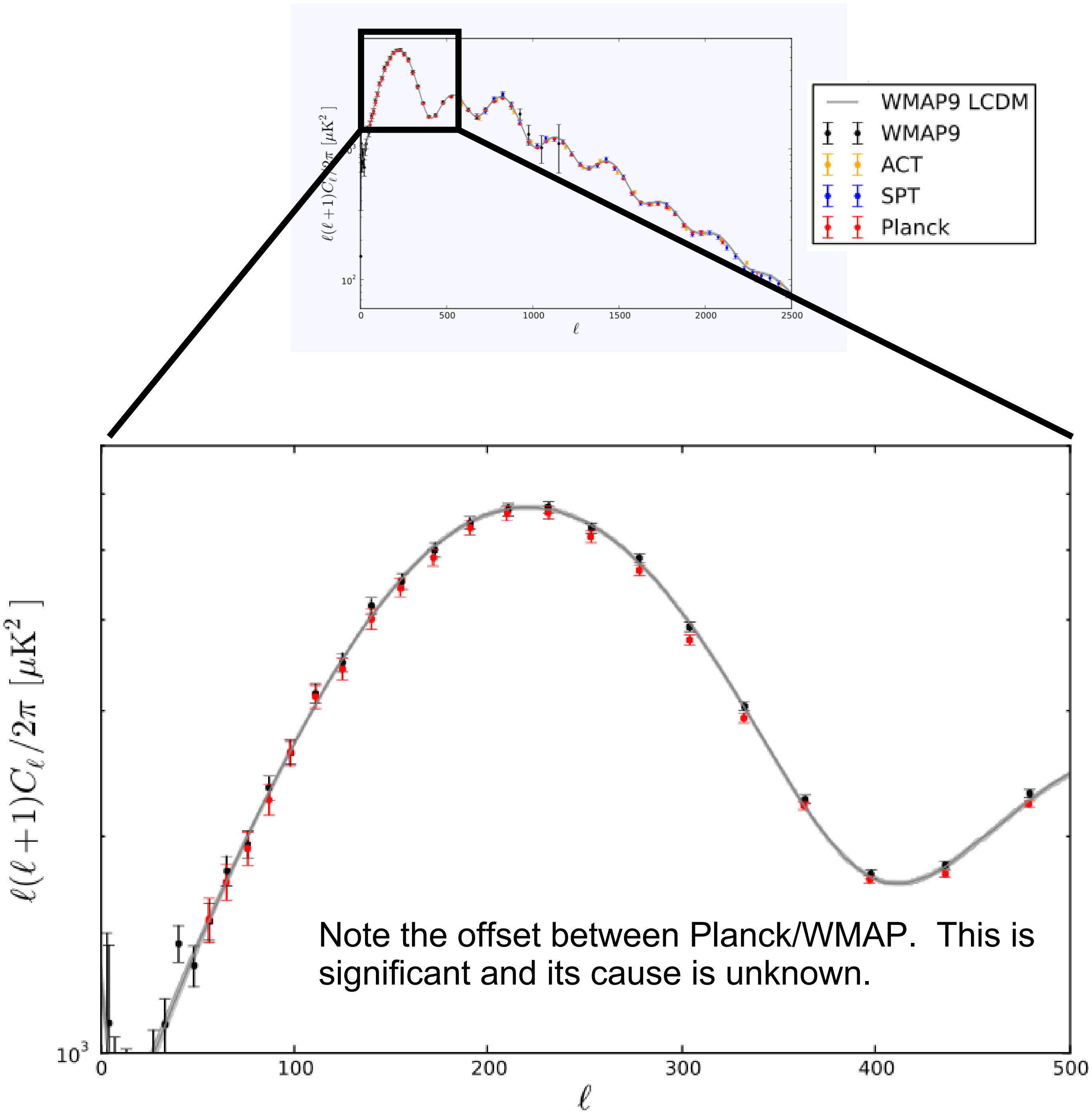
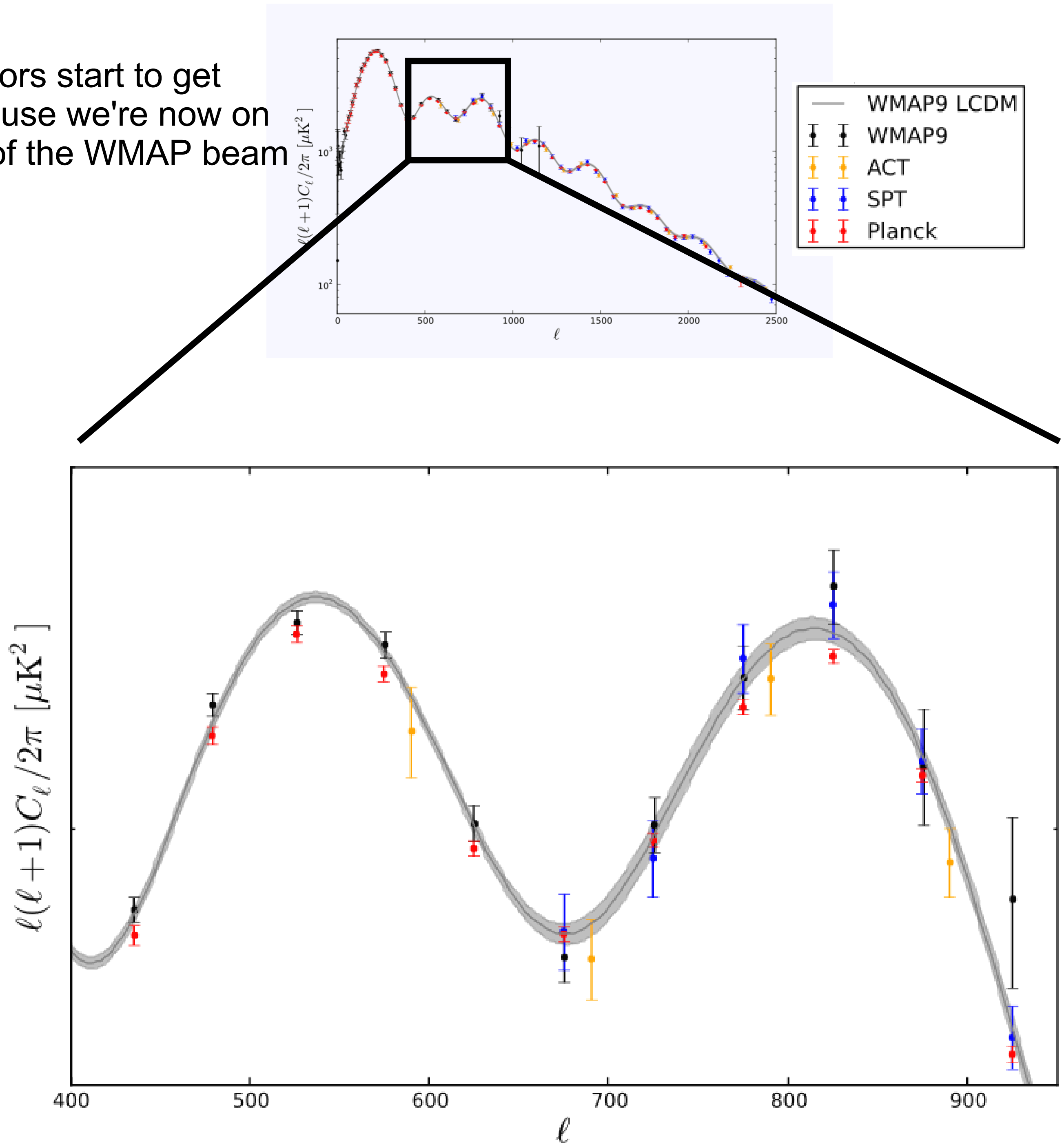
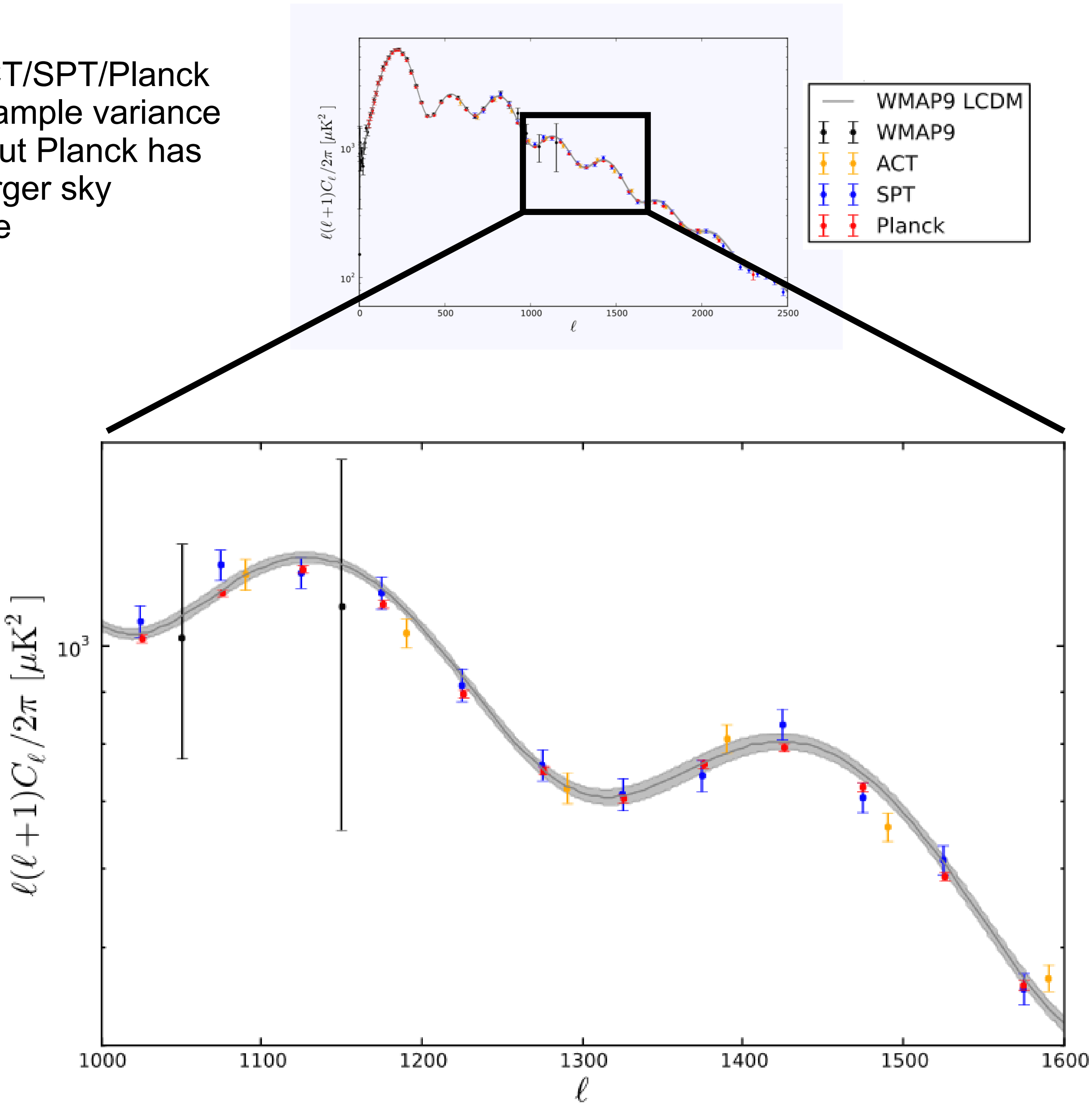
ℓ


WMAP9 LCDM
WMAP9
ACT
SPT
Planck
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
ℓ
Note the offset between Planck/WMAP. This is significant and its cause is unknown.

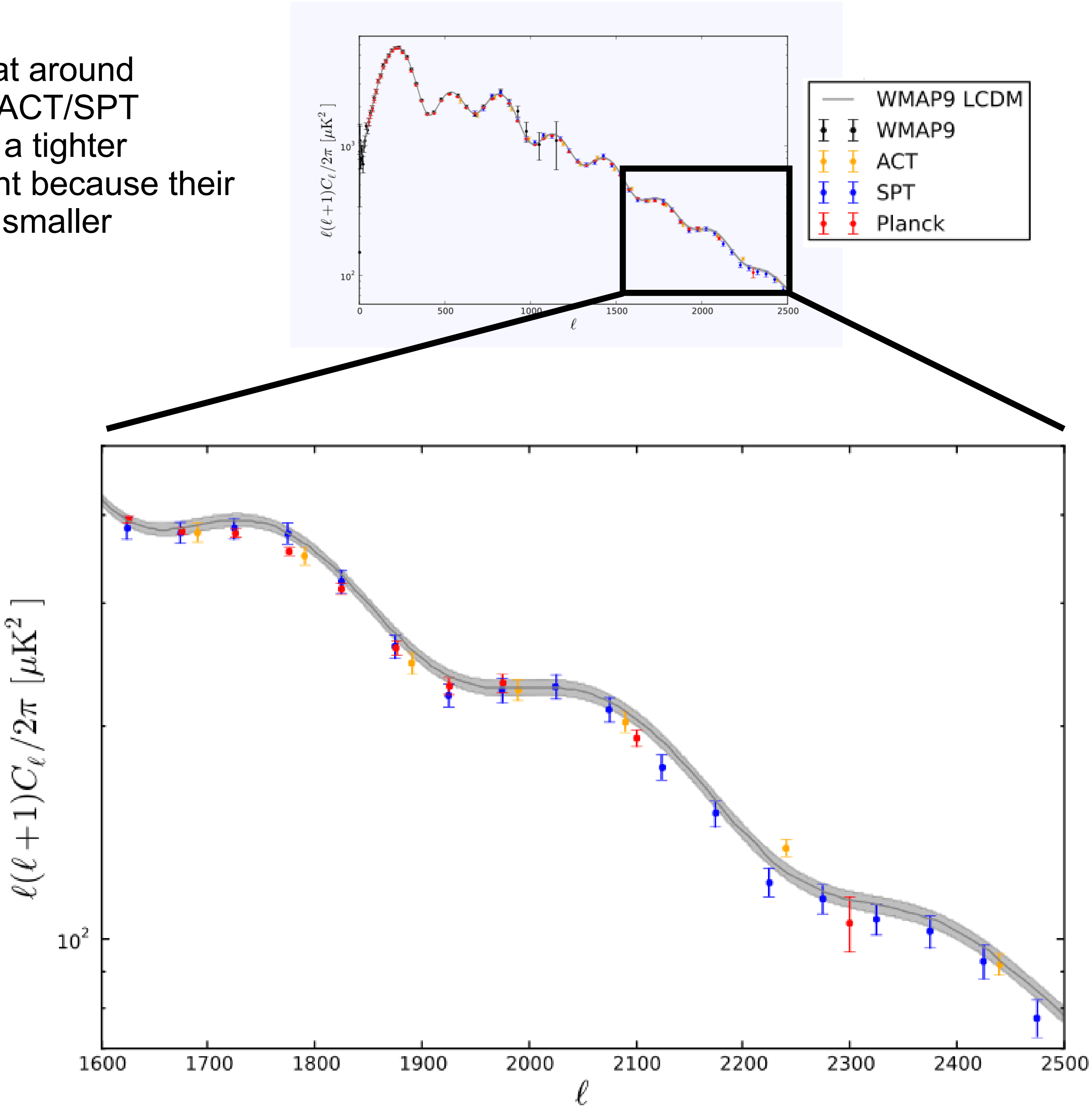
- WMAP errors start to get large because we're now on the scale of the WMAP beam

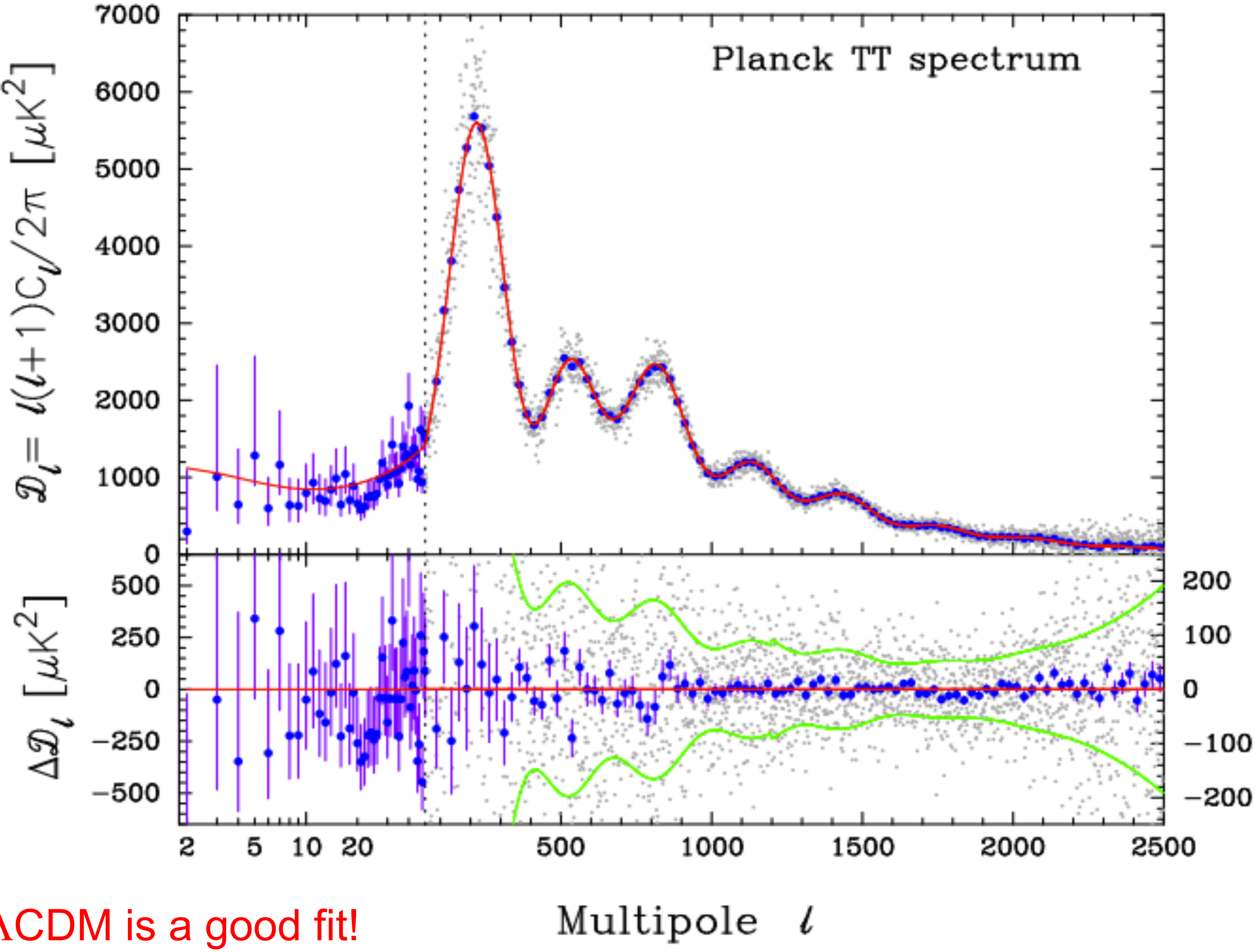


- Here ACT/SPT/Planck are all sample variance limited but Planck has much larger sky coverage



- Finally, at around l=2000, ACT/SPT become a tighter constraint because their beam is smaller

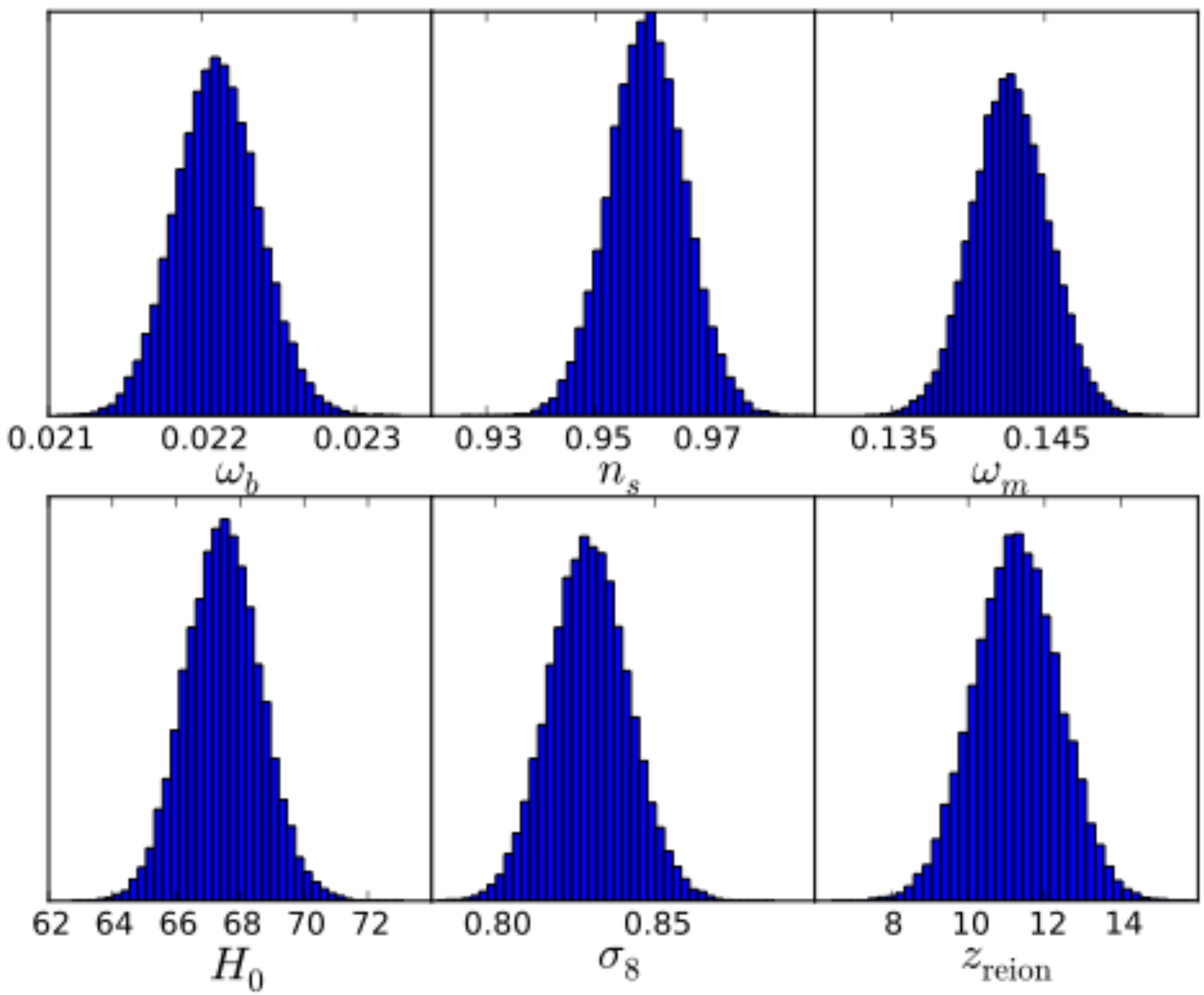




ΛCDM is a good fit!

Parameter constraints

The Planck data provide tight constraints on the six parameters describing the ΛCDM model, and thus on derived parameters.



Parameters in the LCDM model

Parameter	*Planck*		*Planck*+lensing		*Planck*+WP	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

Derived

Parameters in the LCDM model

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
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n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	[illegible]
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± [illegible]12
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 [illegible]
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 [illegible]
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	2.196 [illegible]
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0[illegible]
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± [illegible]57
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± [illegible]012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 [illegible]48
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 [illegible]54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.7[illegible]60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04[illegible]0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063

Derived

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Universe Older, Wider Than Previously Thought

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Astronomers determined that the universe is actually 13.8 billion years old, about 80 to 100 million years older than previously believed, and that it is also a bit wider than once thought. What do *you* think?

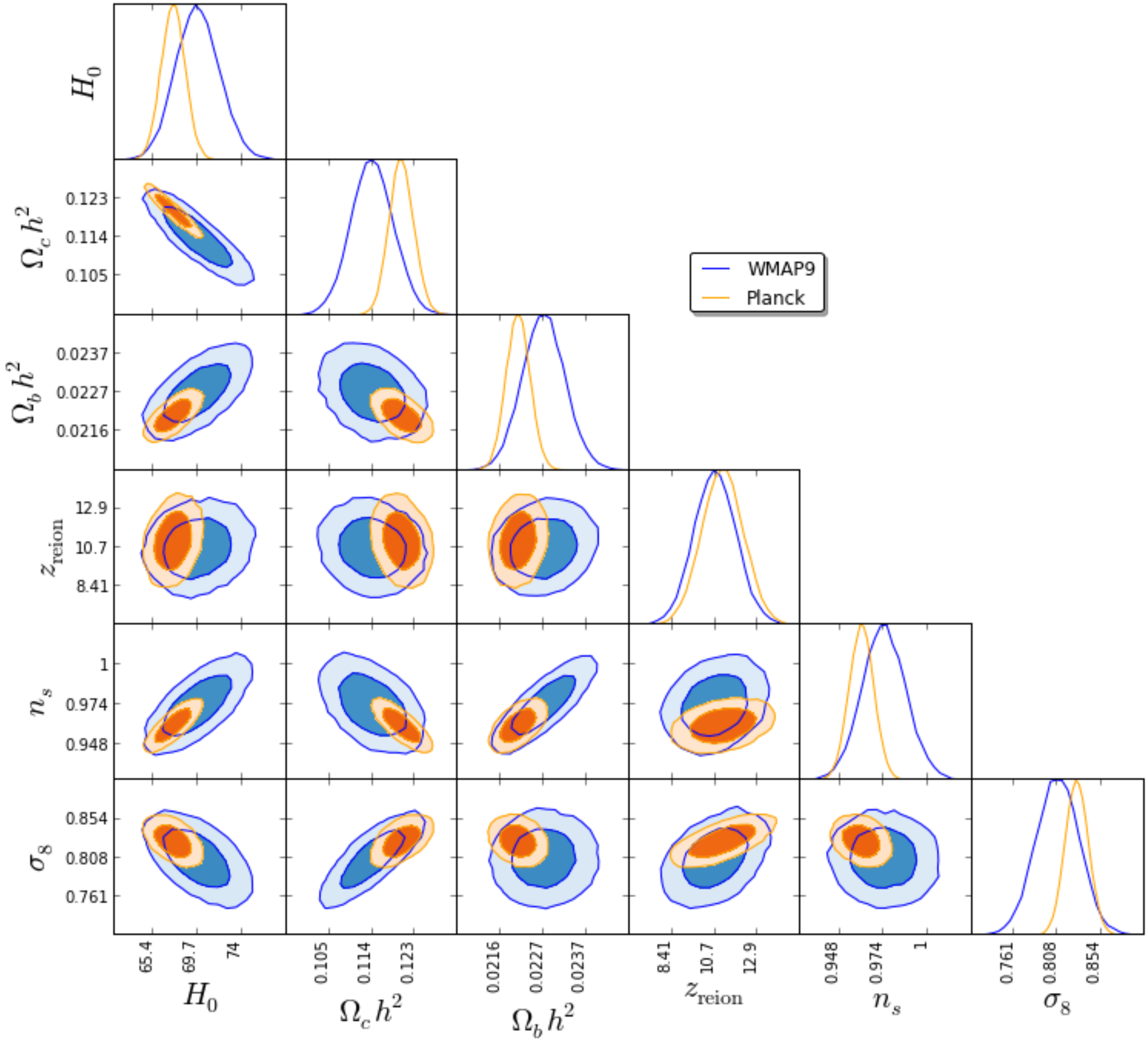
"How embarrassing."

Victoria Rosegard – Street Cleaner

"Typical. You give birth to a few trillion galaxies and then people just talk about how old and fat you've gotten."

"Just like it says in Leviticus."

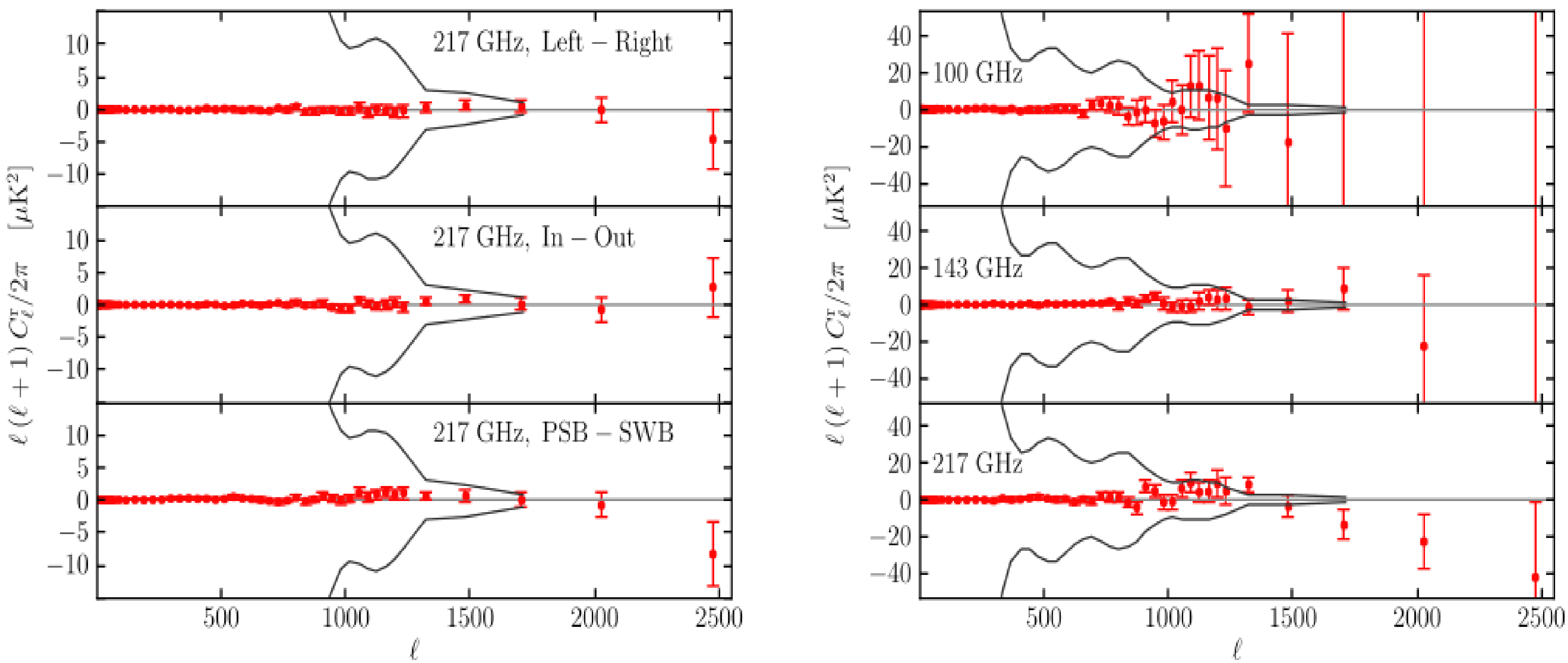
Chris Vanderhorst – Systems Analyst



WMAP9
Planck
H_0
$\Omega_c h^2$
$\Omega_b h^2$
z_{reion}
n_s
σ_8
65.4
69.7
74
0.105
0.114
0.123
0.0216
0.0227
0.0237
8.41
10.7
12.9
0.948
0.974
1
0.761
0.808
0.854

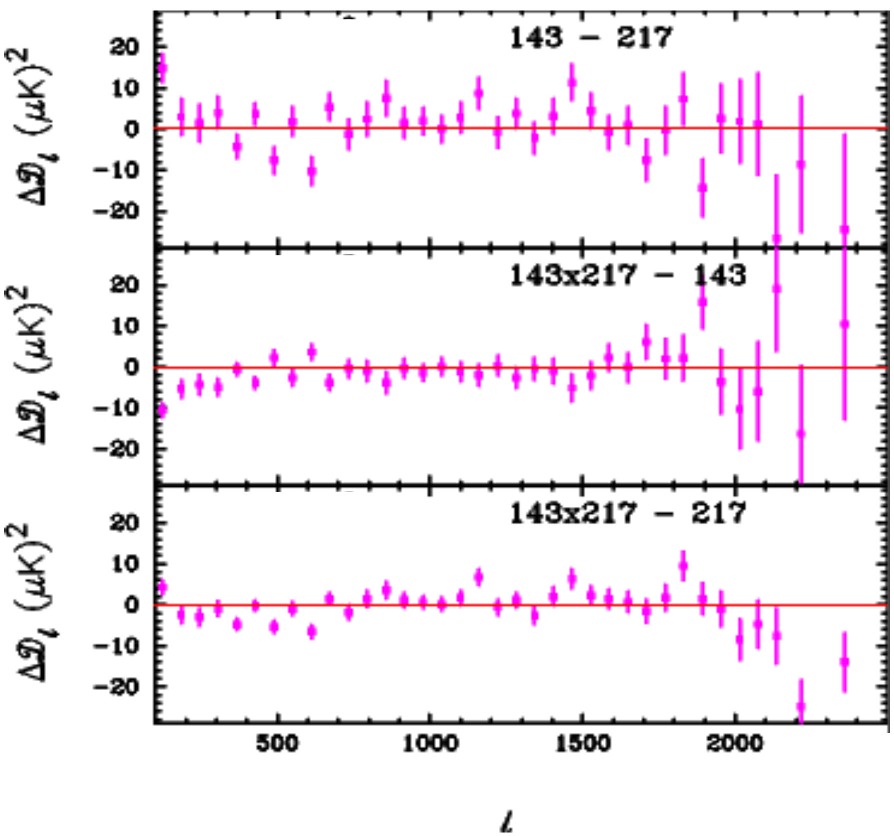
Consistency Tests Within Same Frequency

Null Tests

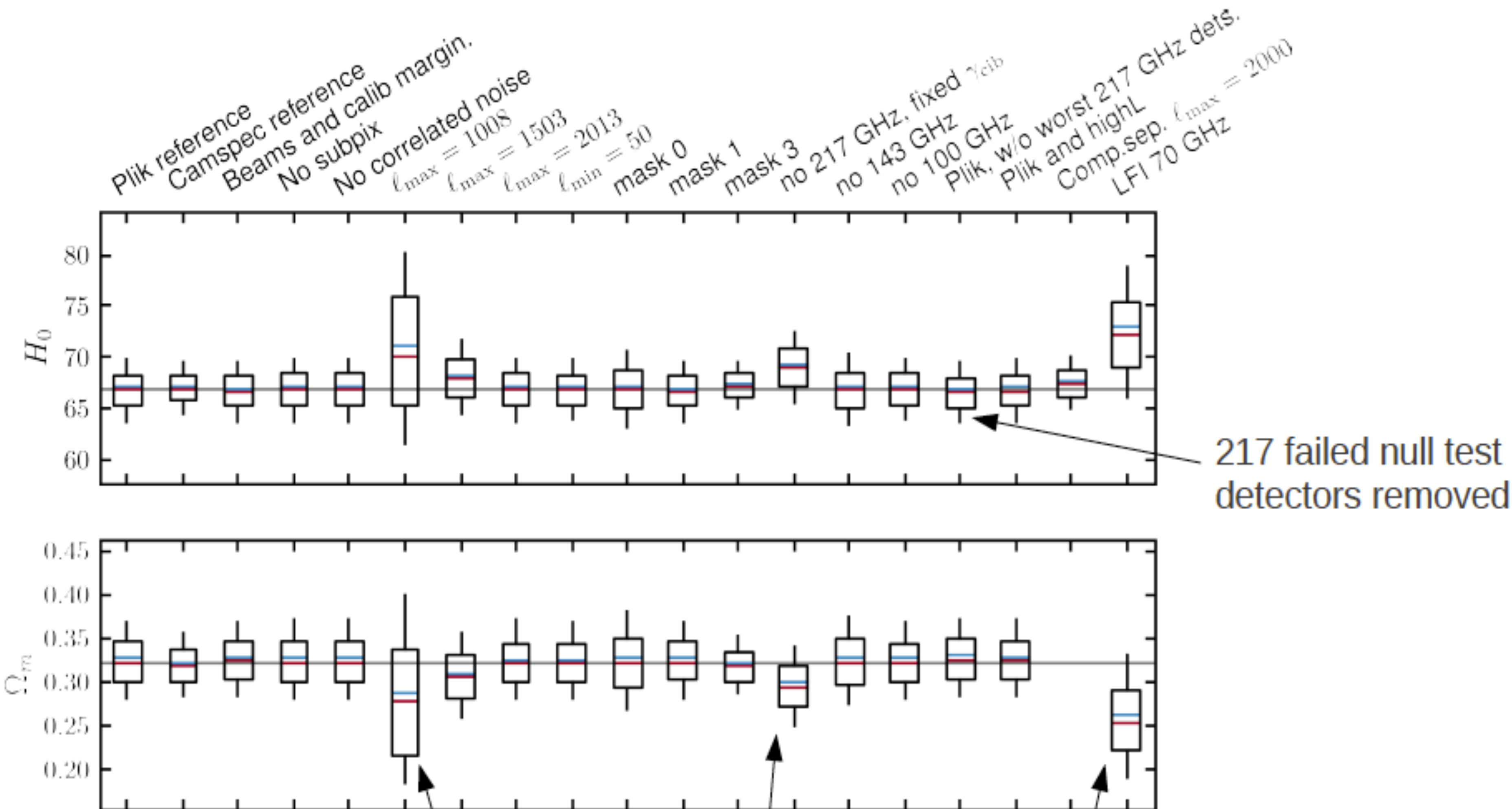


Consistency Tests Between Different Frequencies

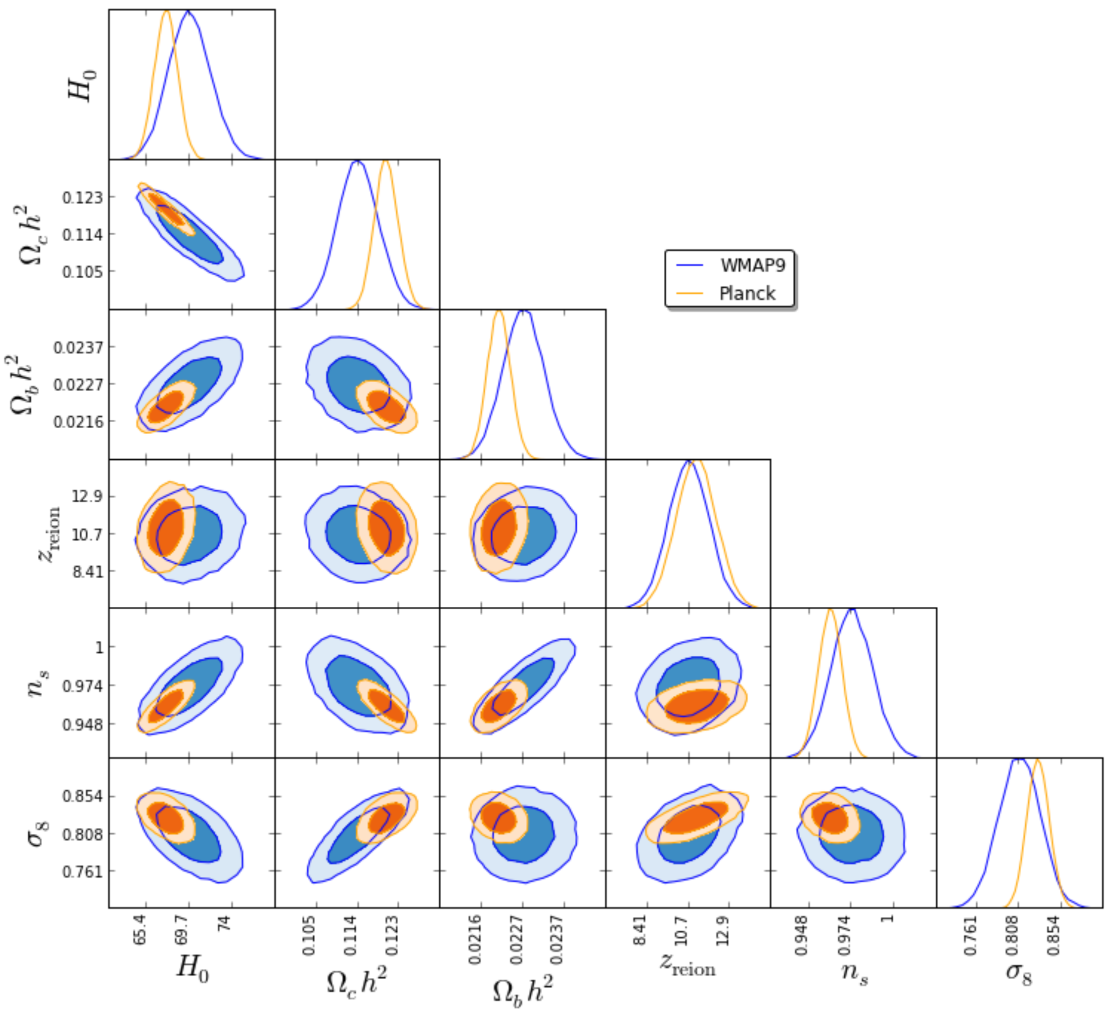
- In units of μK, the CMB is the same at all frequencies
- This is a critical tests of galactic foreground cleaning, extra-galactic foreground modeling, and transfer functions



Effect of modeling choices and data selection



The three things which most significantly affect H0 or Ωm



Should we care?

Do the shifts and decreased errors make any difference?

All Aspects of Cosmology are Touched by the Planck Results

Observation-related Examples:

- BAO-determined distance-redshift relation
- SDSS matter power spectrum
- Deep Lens Survey cosmic shear power spectrum

Consistent*

- Cepheids + SNe for determining H_0
- CFHTLS cosmic shear power spectrum

Some tension*

*Assuming the ΛCDM model

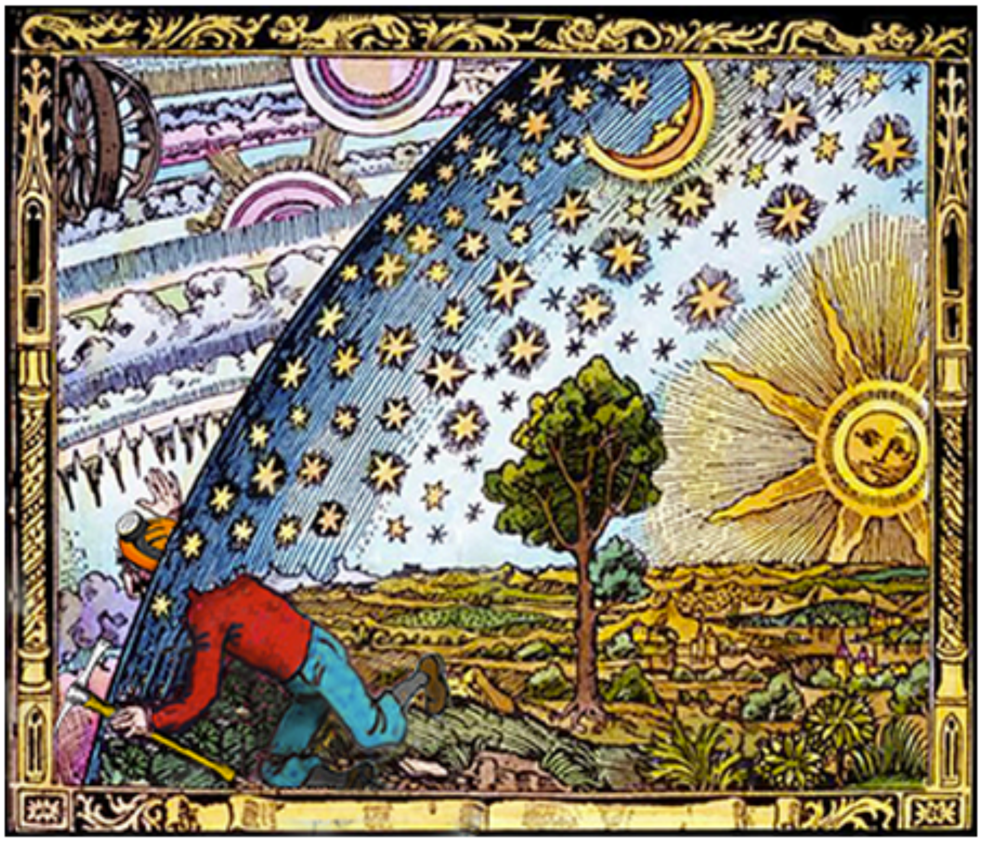
Davis Cosmic Frontiers Conferences

May 20 - 24, 2013

Mining the Cosmic Frontier in the Planck Era
May 20 - 22, 2013

Fundamental Questions in Cosmology
May 22 - 24, 2013

Advertisement



These conferences are supported in part by the UC Davis High Energy Frontier Theory Initiative and Carolyn and Timothy Ferris through the Swig Foundation

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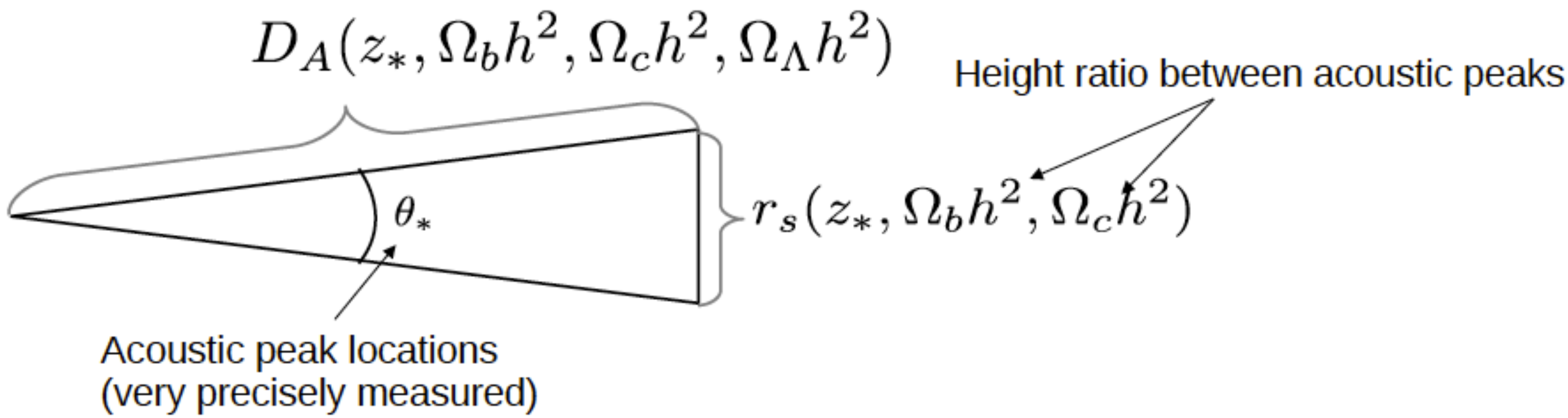
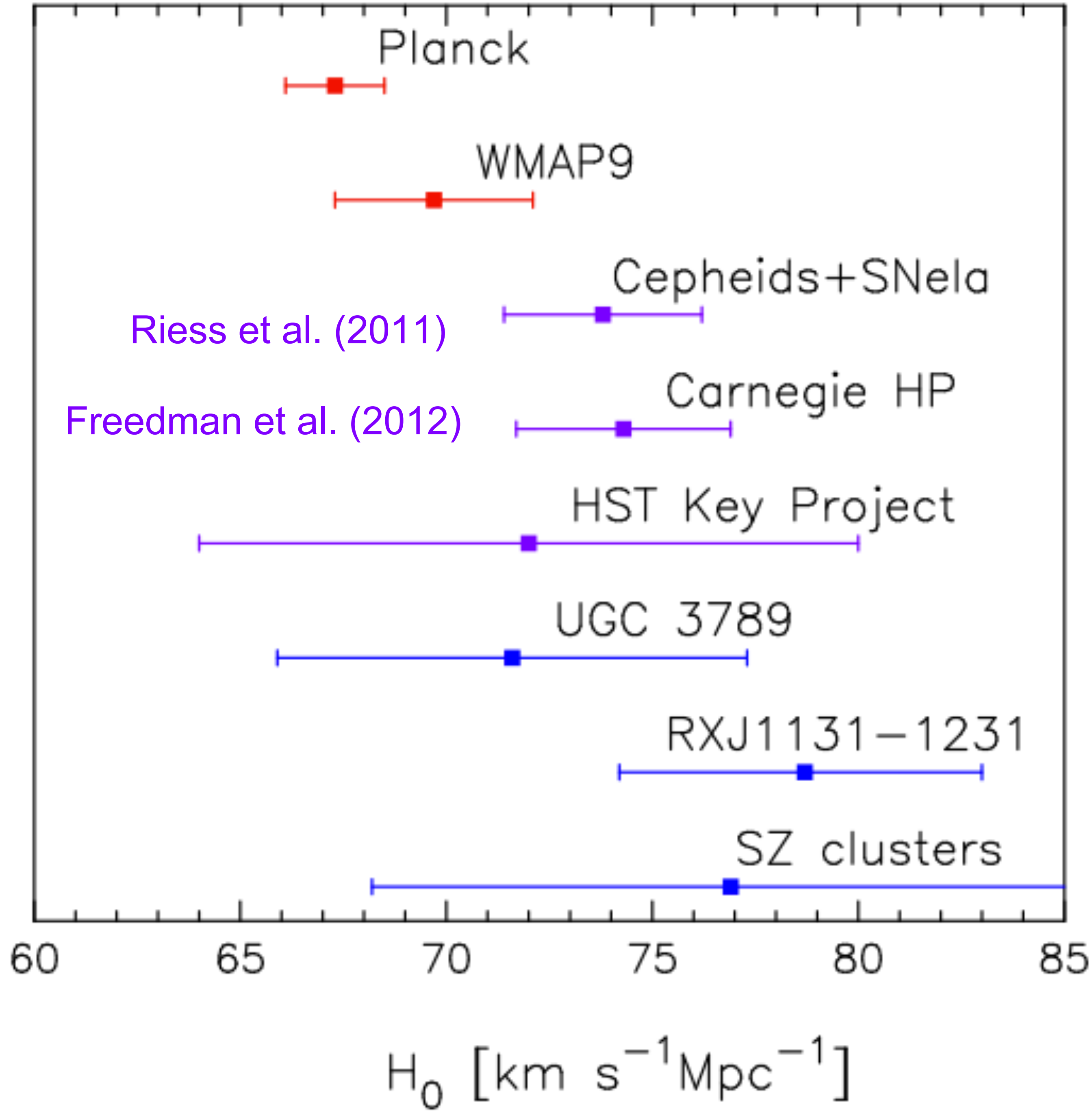
How do we use observations of z = 1100 to determine the expansion rate today, H_0?



z_* = Redshift of last scattering

1) Baryon density = $\Omega_b h^2$ and CDM density = $\Omega_c h^2$ affect peak height ratios*
2) calculate r_s
3) Infer θ_* (=θ_s) from peak locations
4) $D_A = r_s/\theta_*$ thus determined. Only parameter left to vary in LCDM is $\Omega_\Lambda h^2$
5) GR relates expansion rate to total density: $H^2 = 8\pi G\rho/3$


Planck
WMAP9
Cepheids+SNeIa
Riess et al. (2011)
Carnegie HP
Freedman et al. (2012)
HST Key Project
UGC 3789
RXJ1131−1231
SZ clusters
60
65
70
75
80
85
H0 [km s−1Mpc−1]

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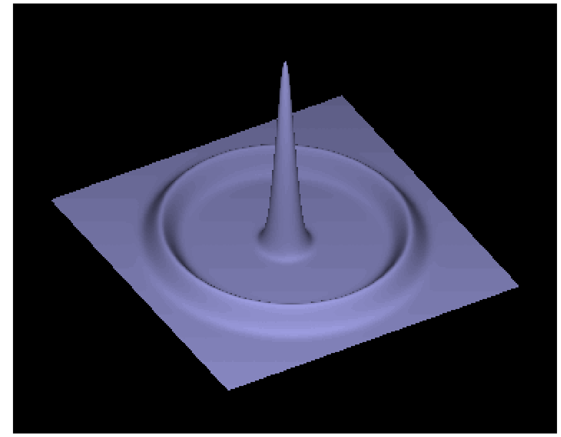
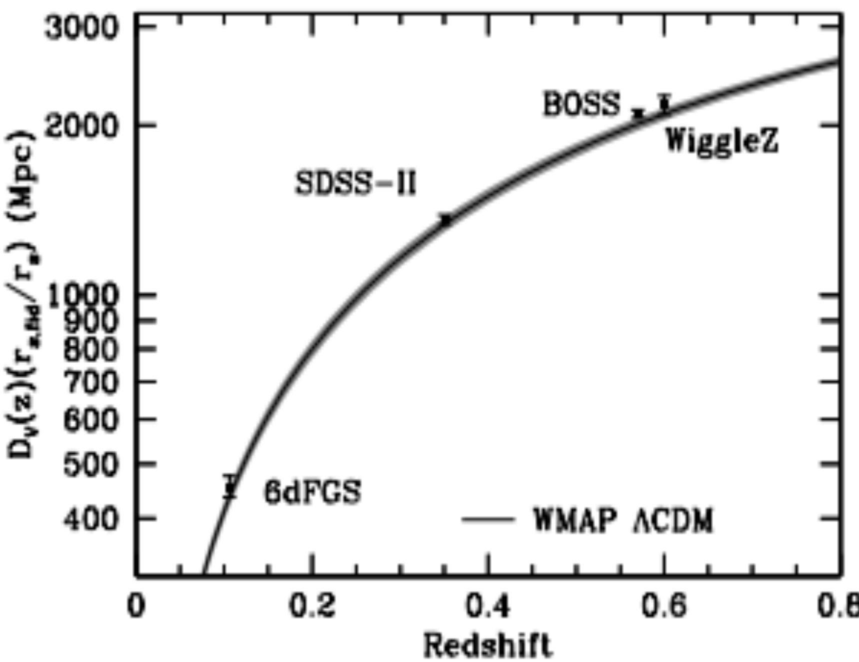
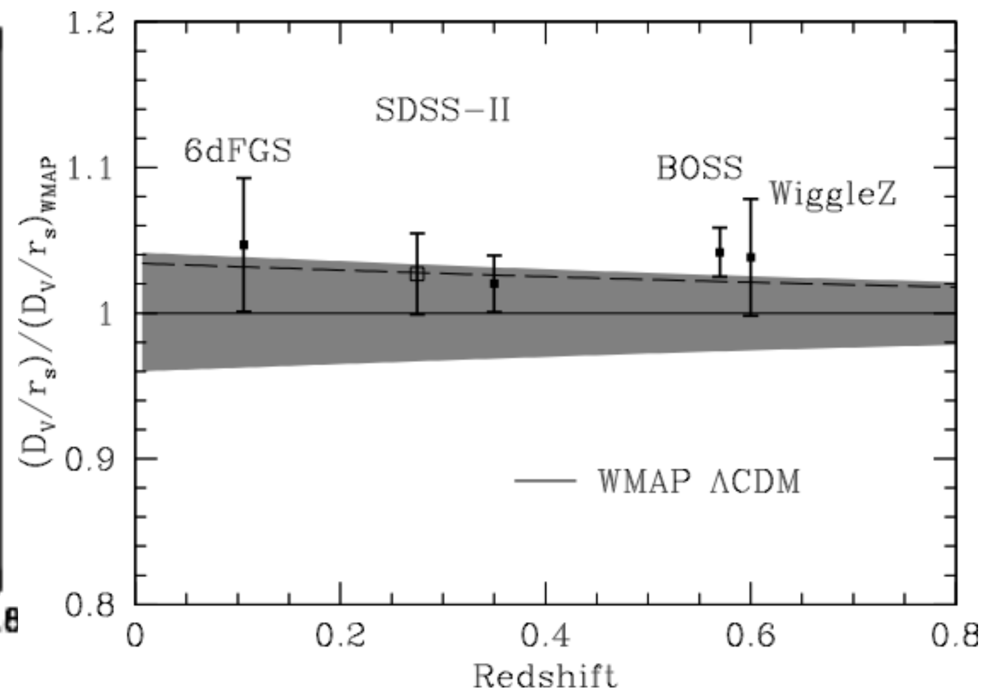
BAO: Exploiting acoustic feature in the galaxy power spectrum

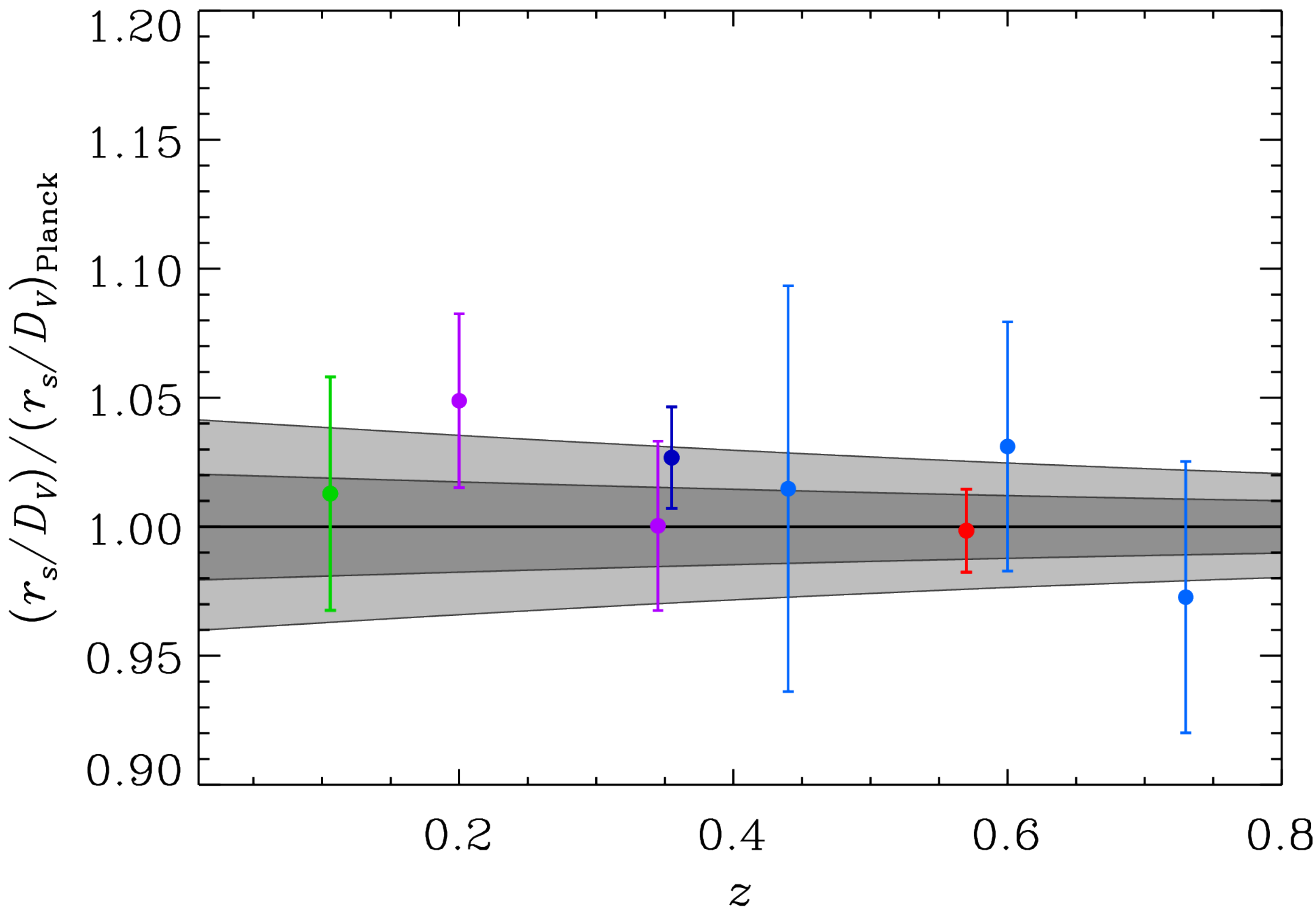






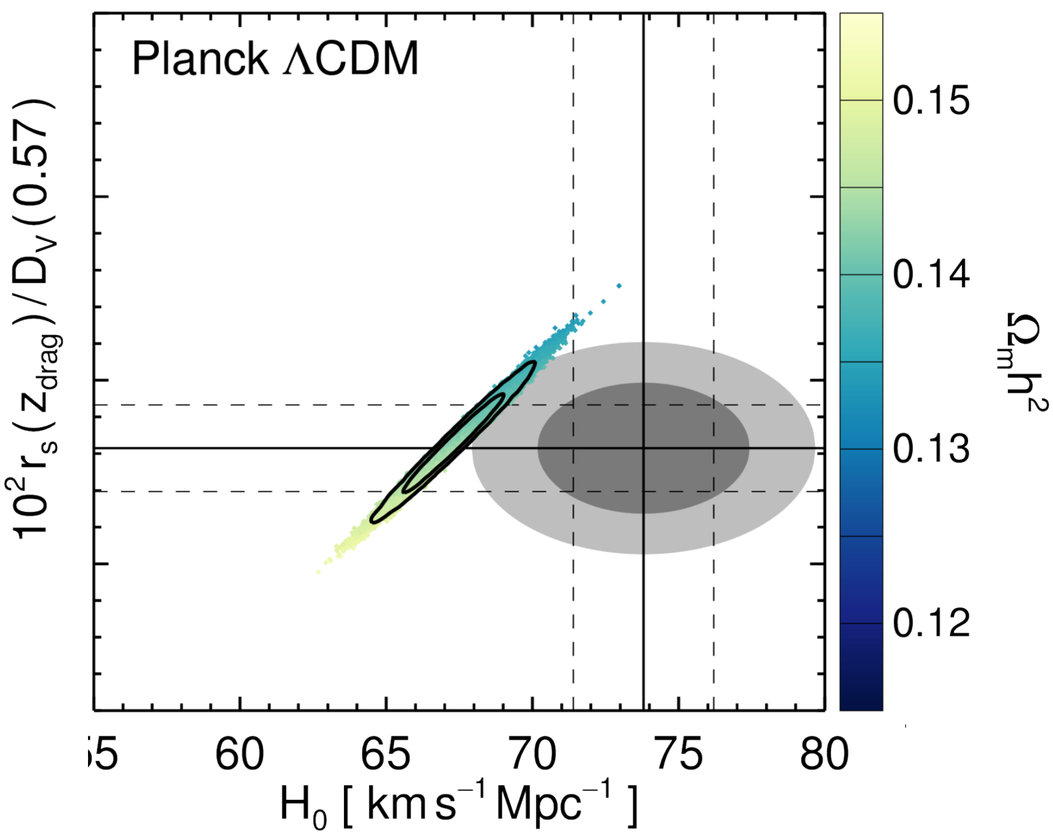
Anderson et al. 2012 (BOSS)

Planck LCDM predictions for BAO and BAO measurements



BOSS BAO, Riess et al. (2011) H_0 and Planck LCDM

- Planck is in excellent agreement with BAO measurement, discrepant with Riess et al. H_0



Beyond LCDM: Neutrinos

Extra Cosmological Neutrinos? Arguments For (slide from April 2012)

- Mild preference for lower damping tail power than in standard cosmological model.
- Measurements of Y have increased in magnitude and uncertainty allowing $N_{eff} = 4$ to be consistent with BBN and perhaps preferred (Izotov & Thuan 2010, Aver, Olive & Skillman 2010, 2011)
- Oscillation evidence for sterile neutrinos from mini-Boone / LSND / Minos
- Oscillation to sterile neutrinos can explain reactor anomalies too.

Personal ads on the arXiv

6. arXiv:1006.5276 [pdf, ps, other]

Cosmology seeking friendship with sterile neutrinos

Jan Hamann, Steen Hannestad, Georg G. Raffelt, Irene Tamborra, Yvonne Y.Y. Wong

Comments: 4 pages, 1 figure, matches version published in PRL

Journal-ref: Phys.Rev.Lett.105:181301,2010

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Cosmology and Extragalactic Astrophysics (astro-ph.CO)

(But not yet in PRL)

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Cosmology Favoring Extra Radiation and Sub-eV Mass Sterile Neutrinos as an Option

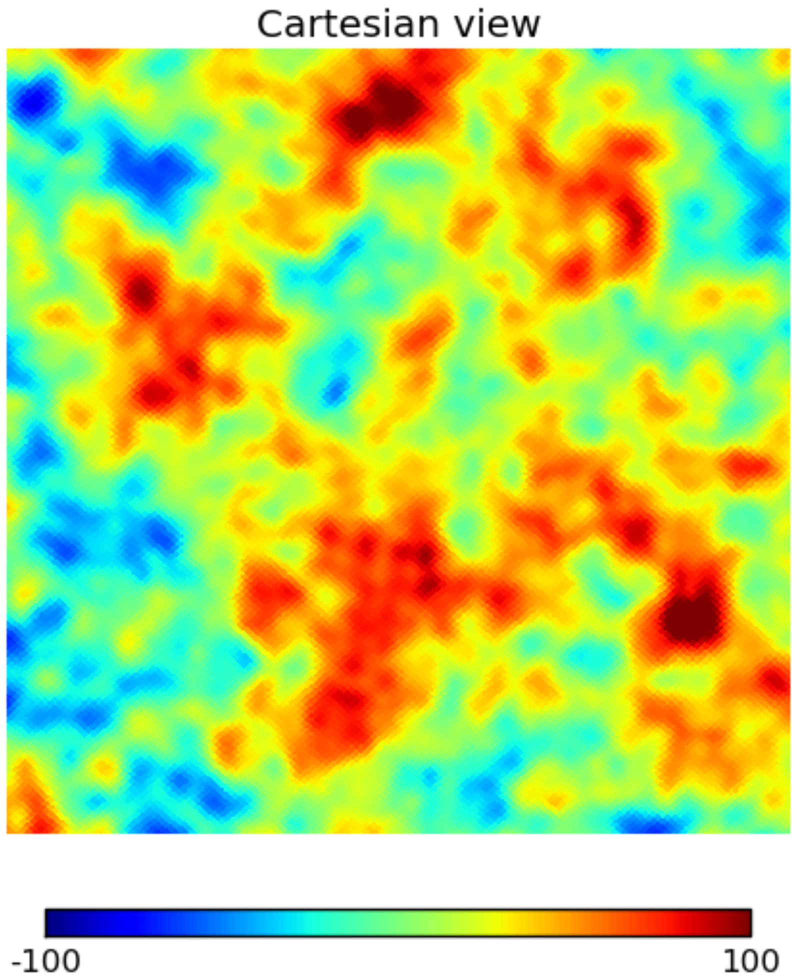
Abstract | References | Citing Articles (10)

Download: PDF (149 kB) Buy this article **Export:** BibTeX or EndNote (RIS)

Jan Hamann[1], Steen Hannestad[1], Georg G. Raffelt[2], Irene Tamborra[2,3,4], and Yvonne Y. Y. Wong[5]

Neff affects the ratio of sound horizon to diffusion scale

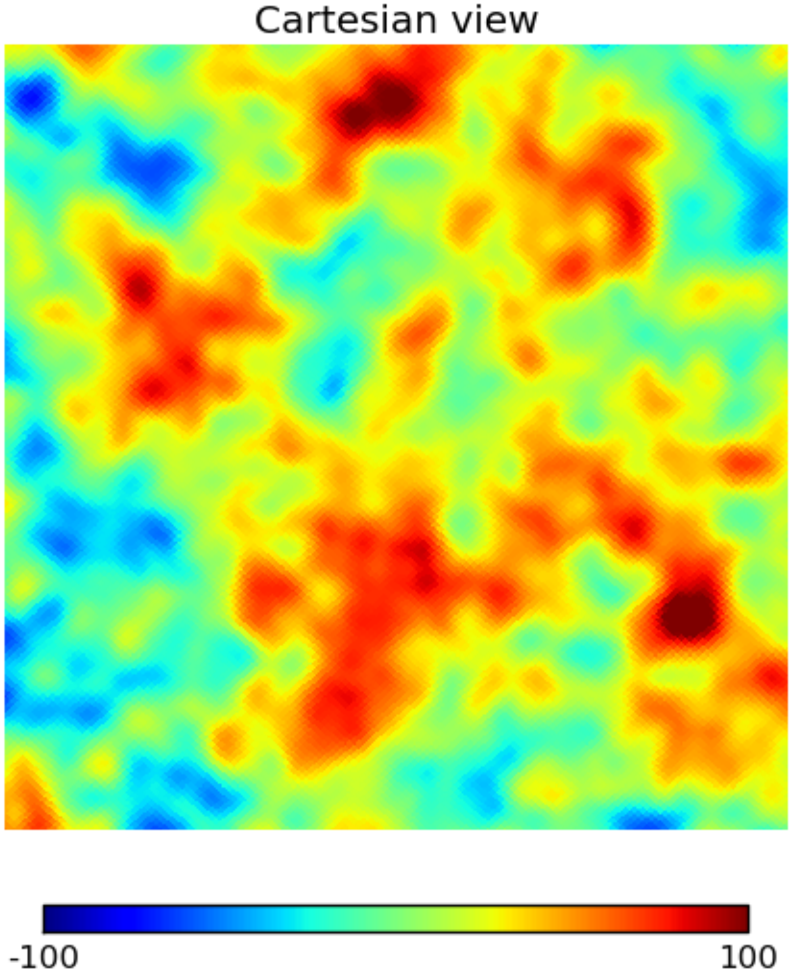
Neff=2
simulated
CMB map



Moon, to scale

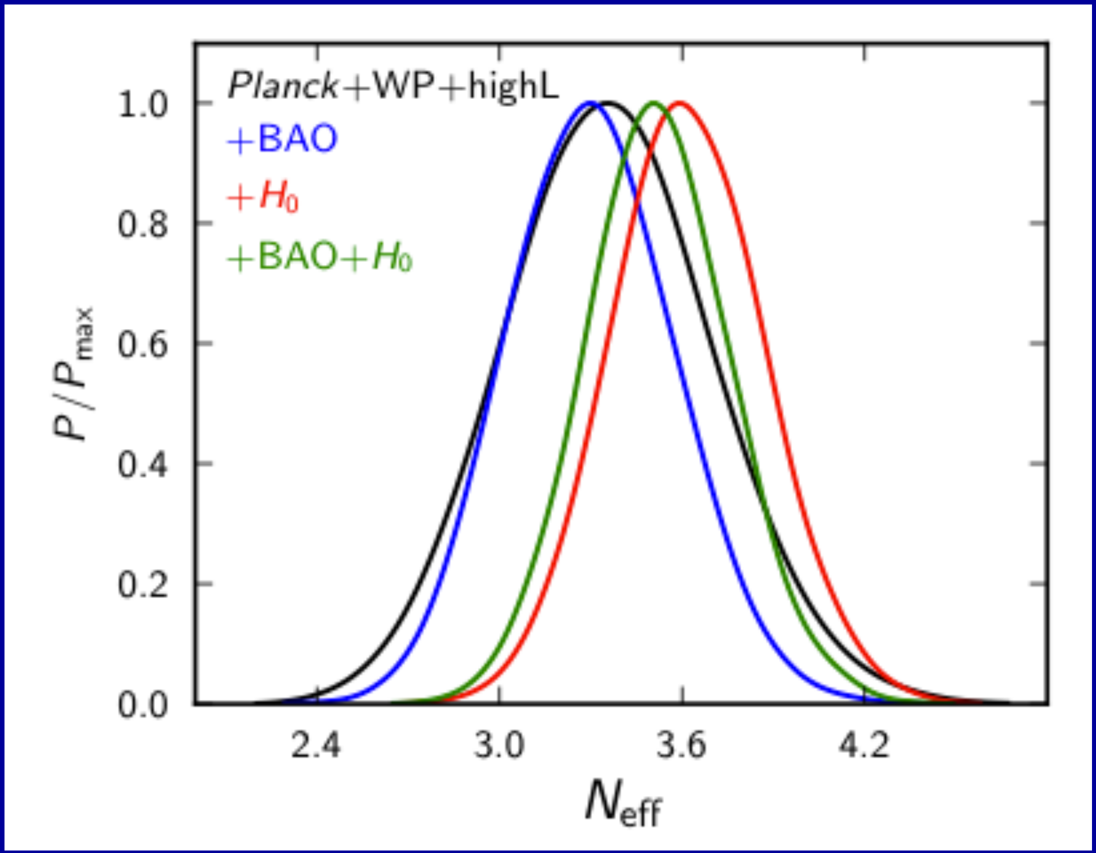
Neff affects the ratio of sound horizon to diffusion scale

Neff=6
simulated
CMB map



Moon, to scale

Light Degrees of Freedom



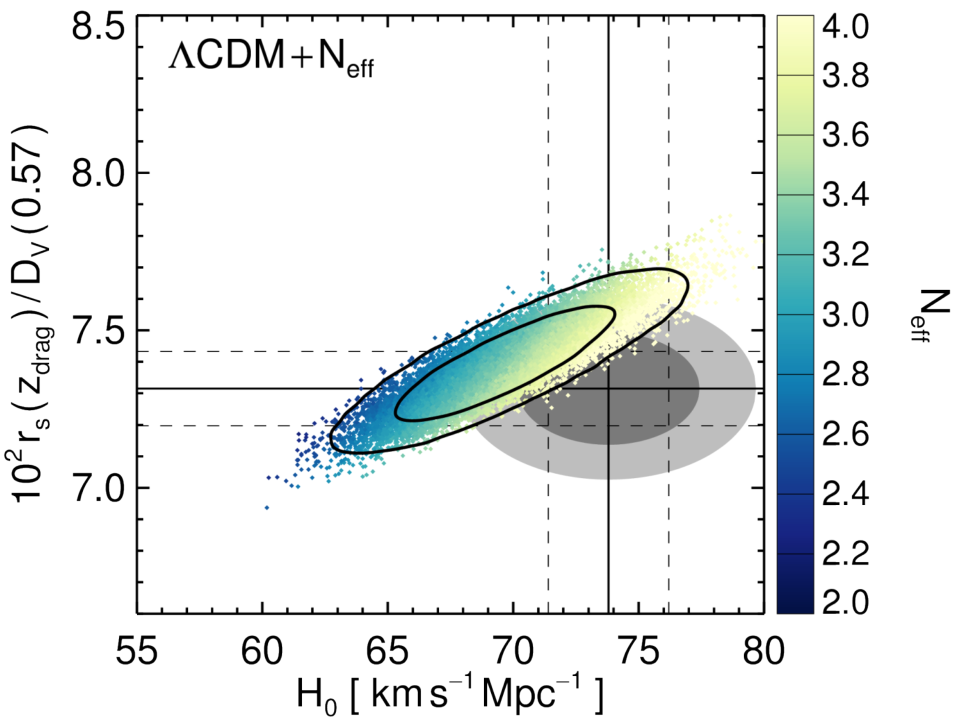
Contribute to the energy density and hence the expansion rate, altering r_s and r_d.

Standard model has Neff = 3.046. No evidence in Planck data, or Planck +BAO for extra species.

Neff > 3 is somewhat preferred by Planck+Riess et al. H_0

Light Degrees of Freedom - Neff

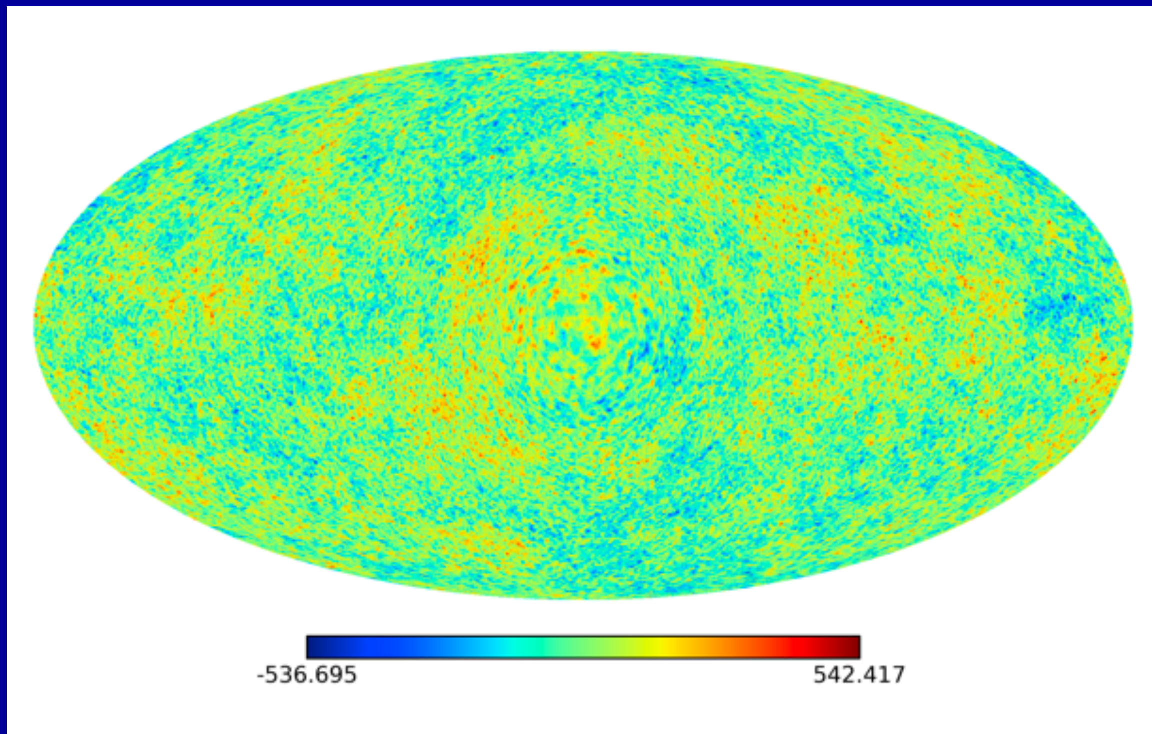
- Increasing Neff, we get better consistency between CMB and Riess et al. H_0 while preserving consistency with BAO.
- Systematic errors or new physics?
- Polarization data will be informative



CMB lensing

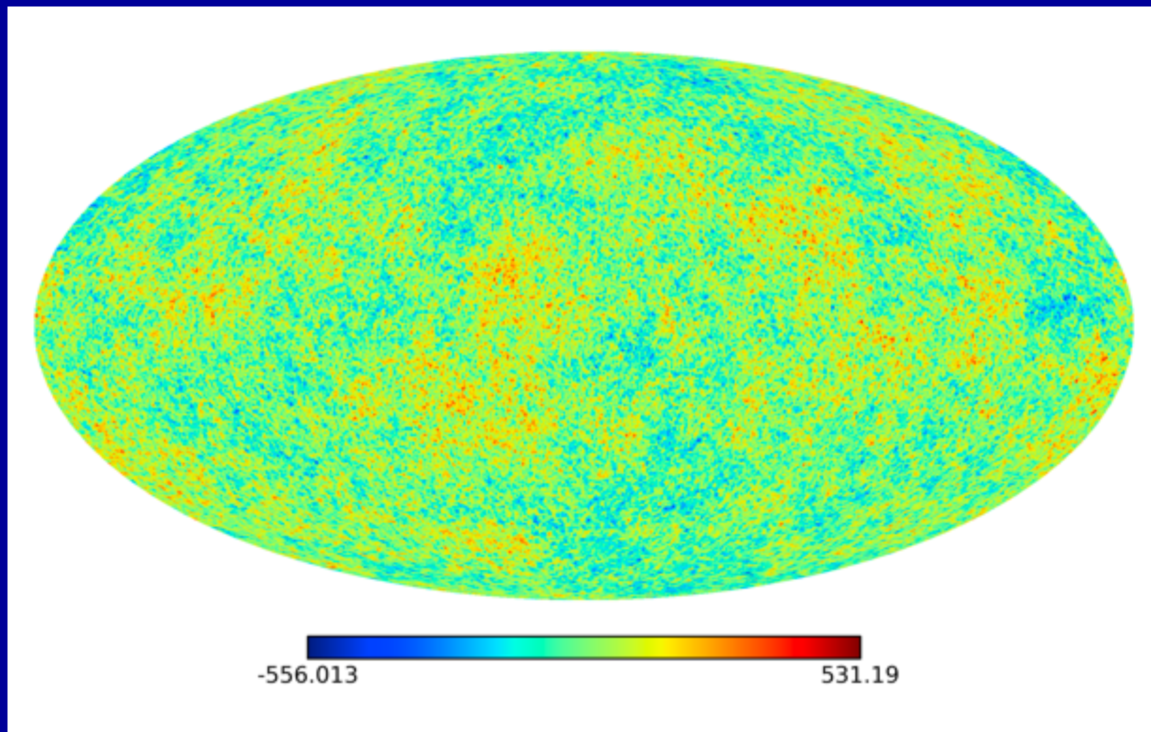
- **Photons from the CMB are deflected on their way to us by the potentials due to large-scale structure.**
- **The typical deflection is 2-3 arcmin.**
- **The deflections are coherent over degrees.**
- **First considered in 1987, first measured in 2004.**
- **Lensing:**
  - **Blurs acoustic peaks (more lensing = smoother peaks).**
  - **Generates small-scale power.**
  - **Generates non-Gaussianity.**
  - **Mixes E- and B-mode polarization.**
- **ACT and SPT detect lensing at 4-6σ.**
- **Planck detects lensing at 25σ (see smearing effect at 10 σ).**
  - **Integrated to LSS, but peak sensitivity z~2.**
  - **Structures of a few Mpc.**

Gravitational Lensing



- ACT and SPT detect lensing at 4-6σ.
- Planck detects lensing at 25σ

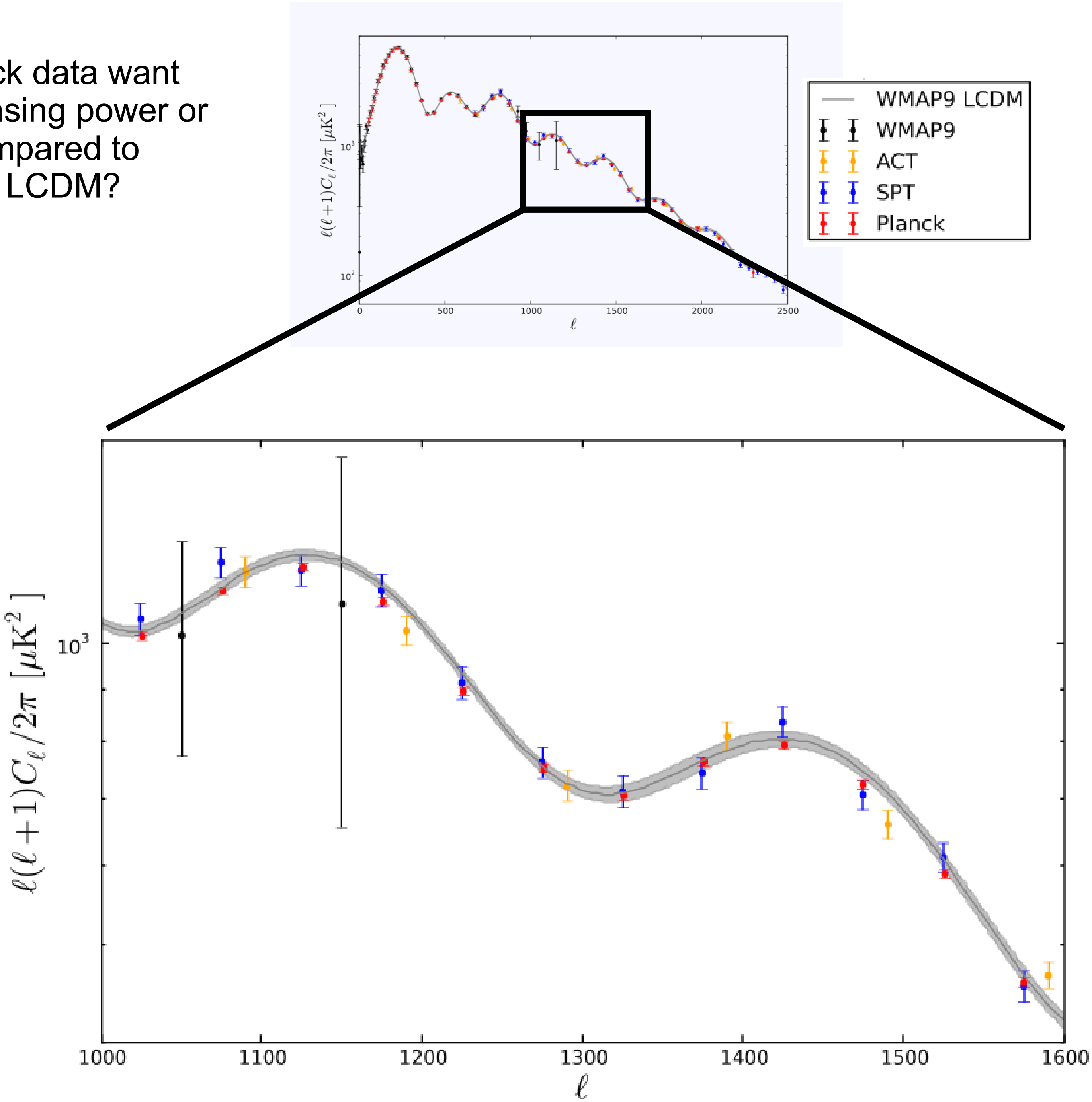
Gravitational Lensing



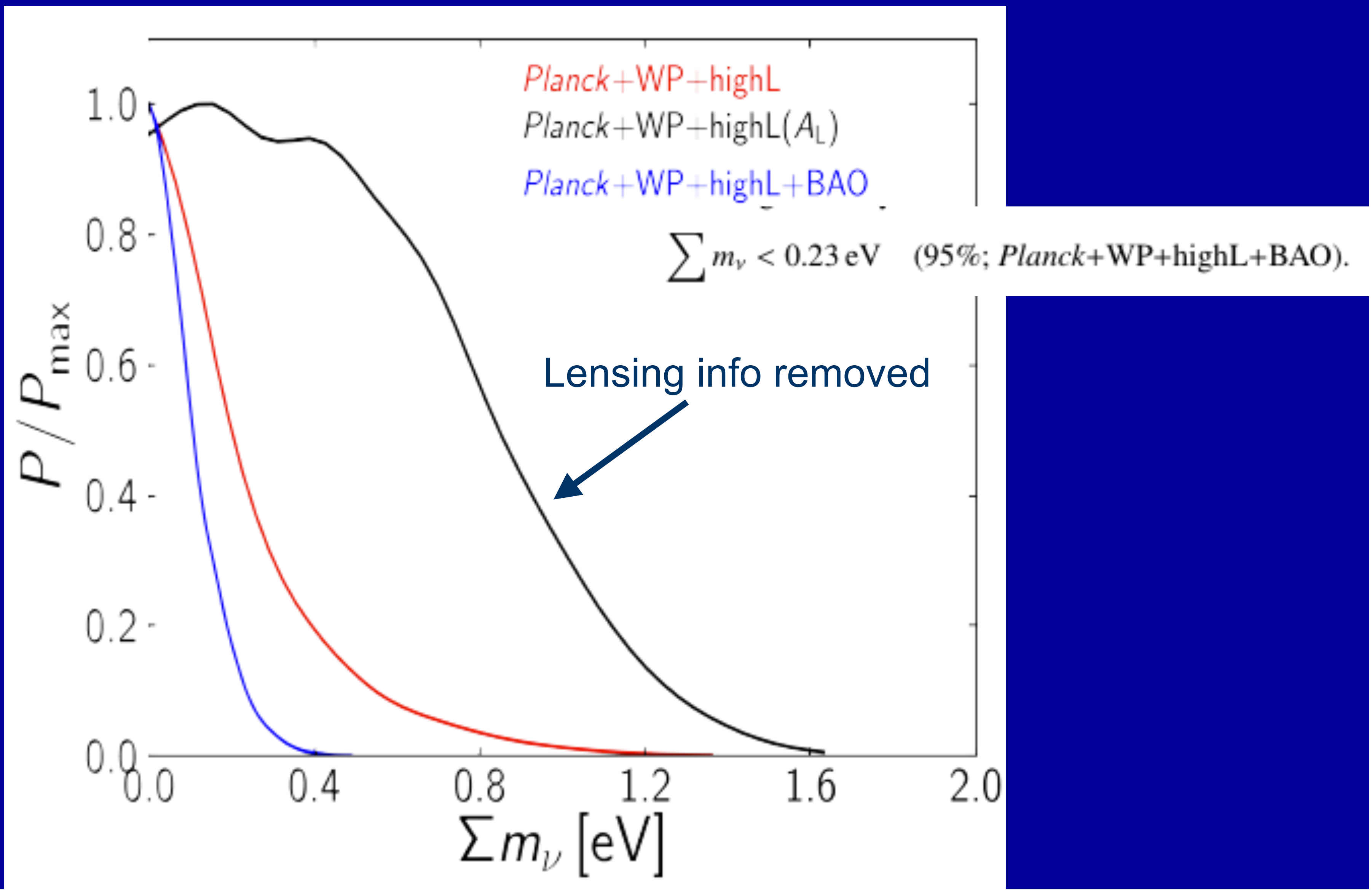
Lensing Application I

The lensing-induced smoothing of the CMB temperature power spectrum and constraints on the sum of neutrino masses

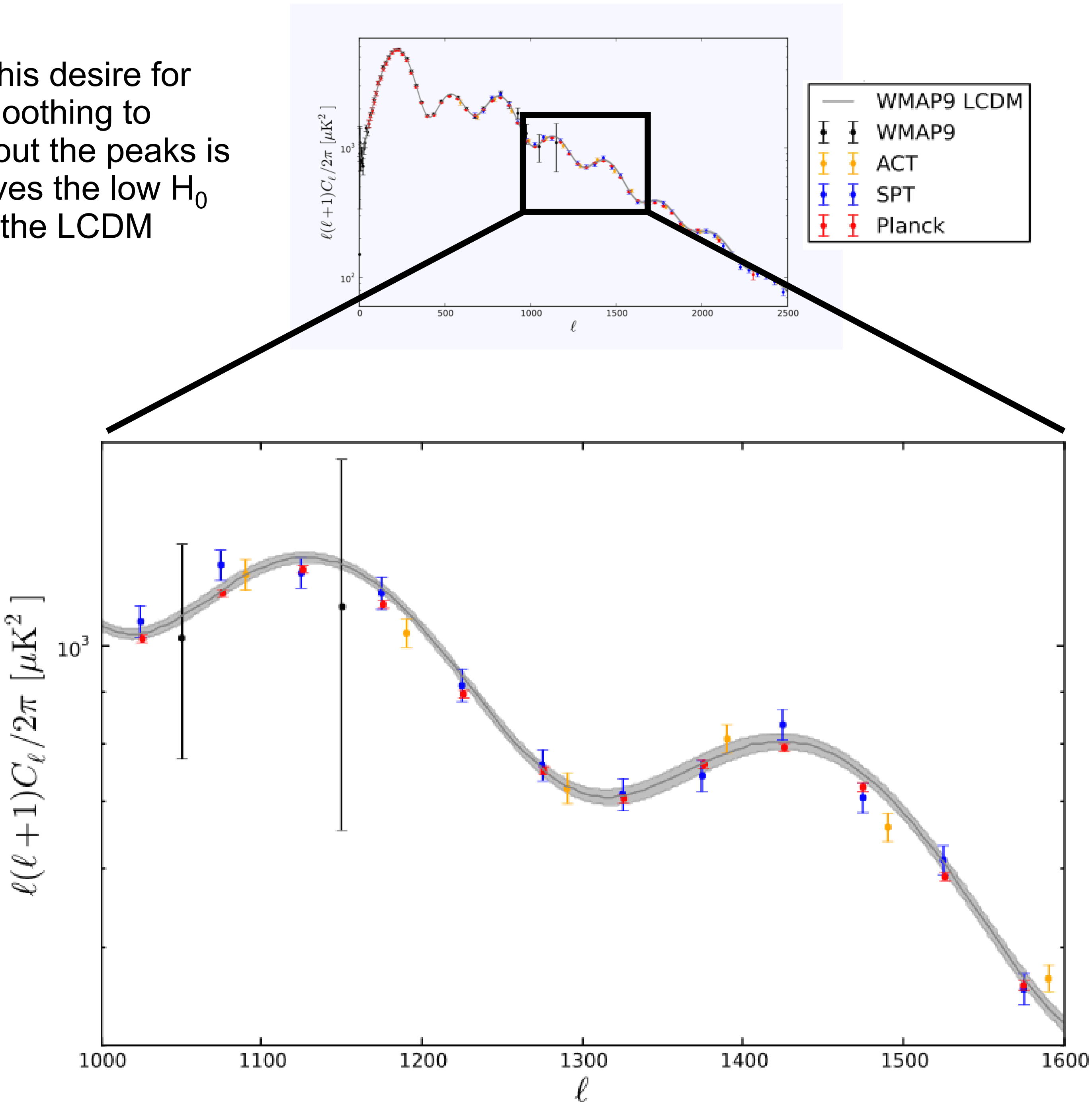
- Do planck data want more lensing power or less, compared to WMAP9 LCDM?



For the first time, lensing information is dominant source of information about m_ν



- BTW: This desire for extra smoothing to smooth out the peaks is what drives the low H_0 result in the LCDM model.



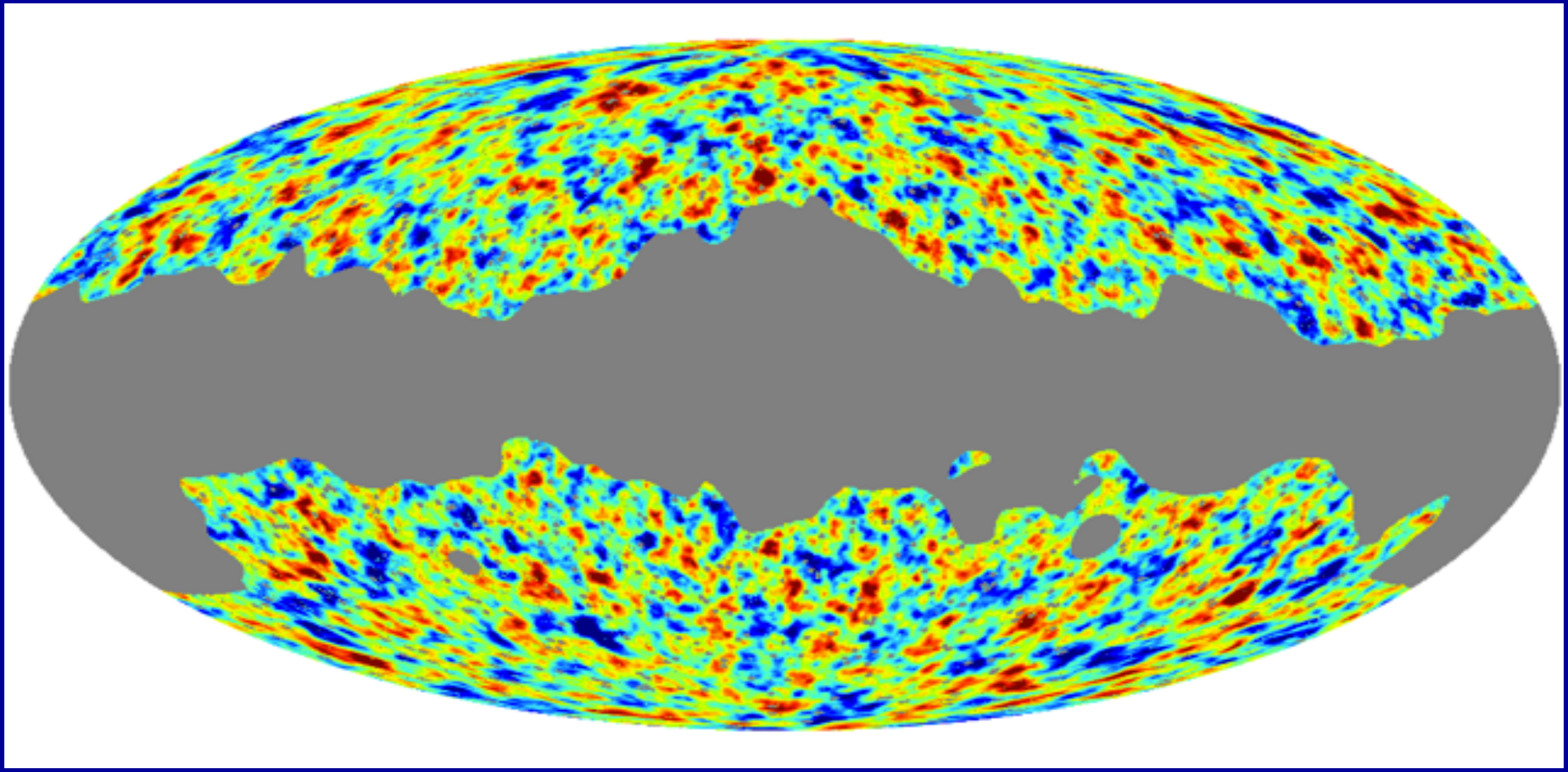
Lensing Application II

Reconstruction of the lensing potential ϕ.

By definition deflection = gradient of ϕ

ϕ is given by a radial projection of the 3D gravitational potential Φ

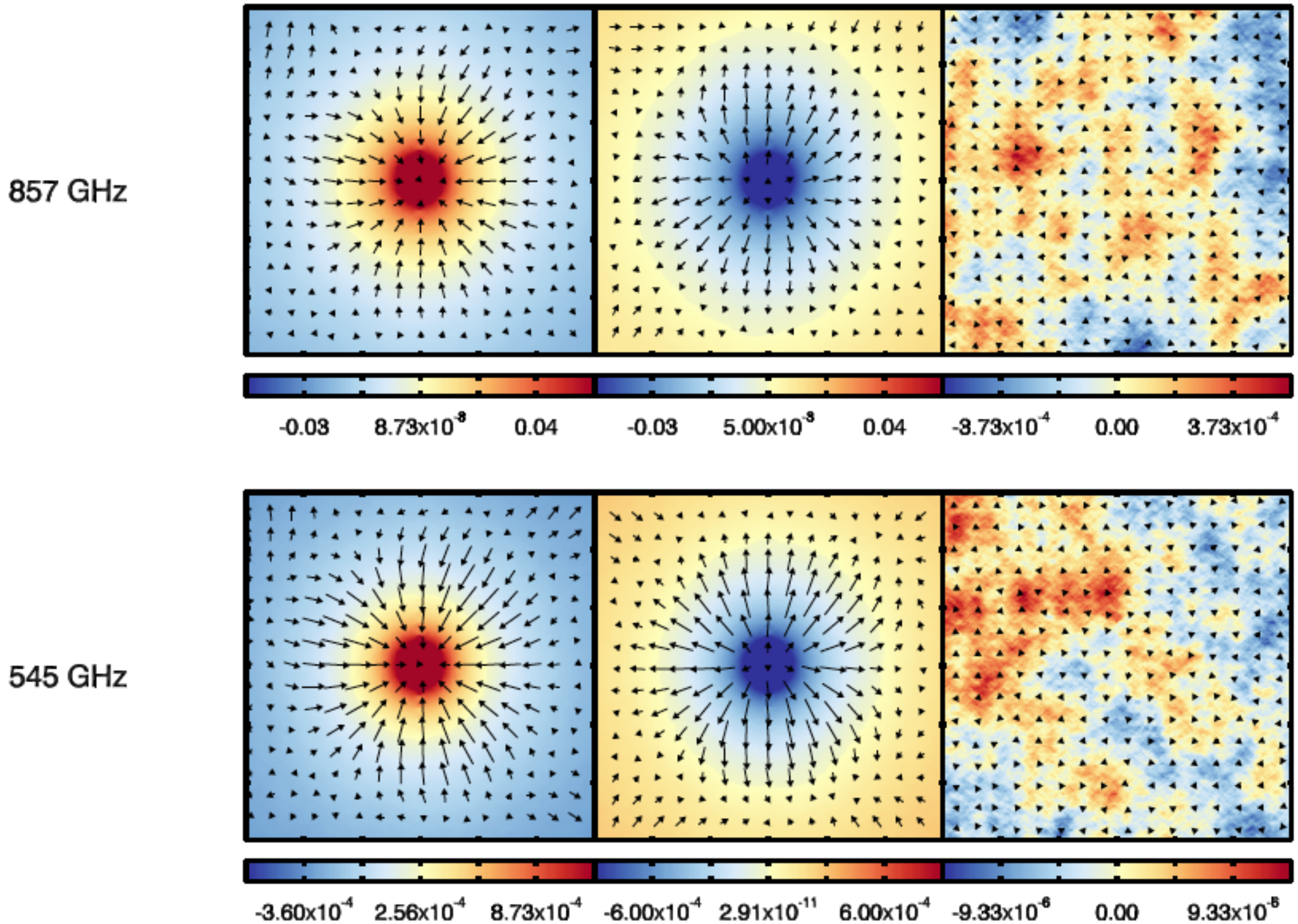
Map of Deflection amplitude



The dusty star-forming galaxies that are the dominant sources of the infrared background correlate with the mass that lenses the microwave background*

Also seen in SPTxHerschel arXiv:1303.5048

*as predicted by Song et al. (2003)

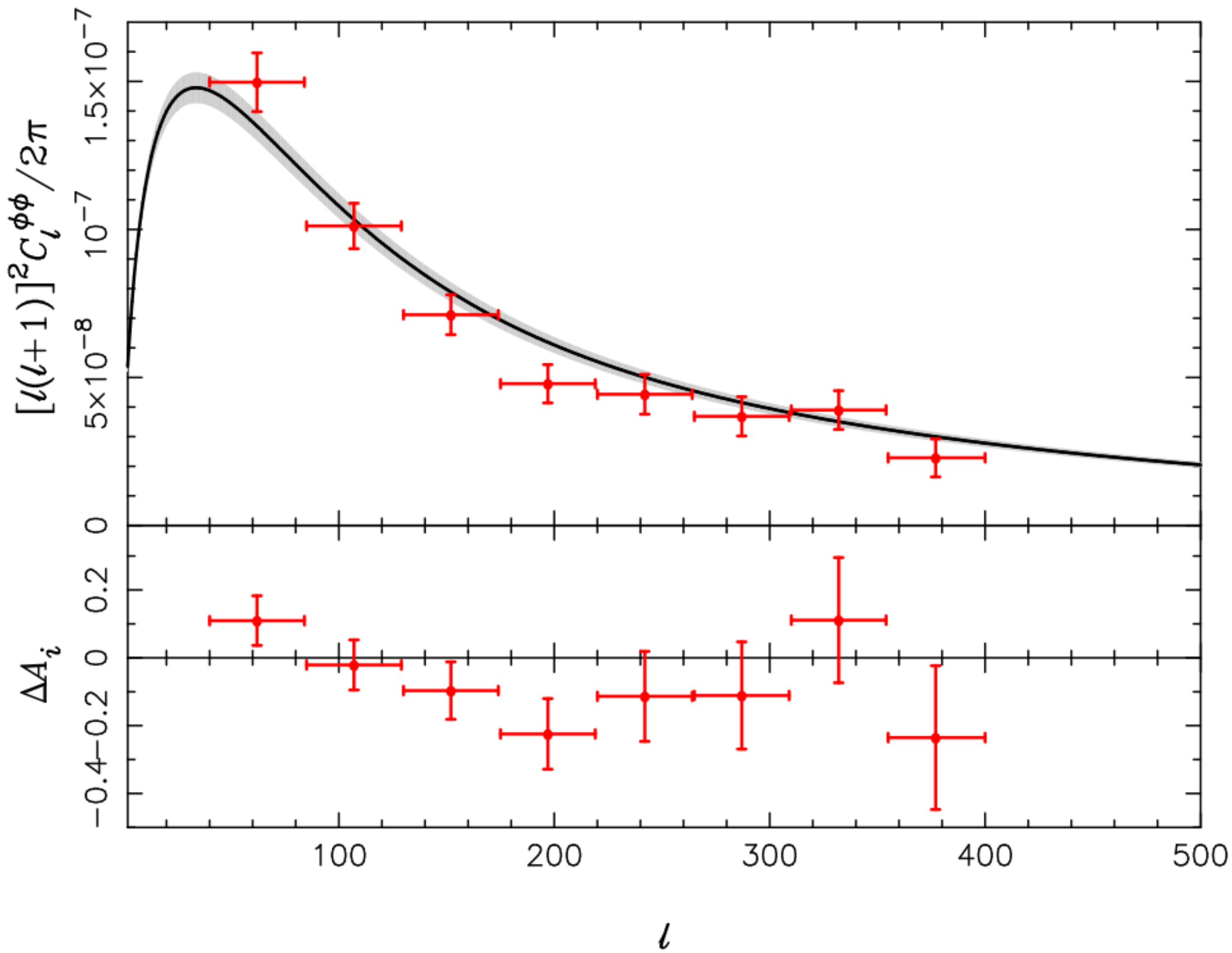


Stacking on hot spots

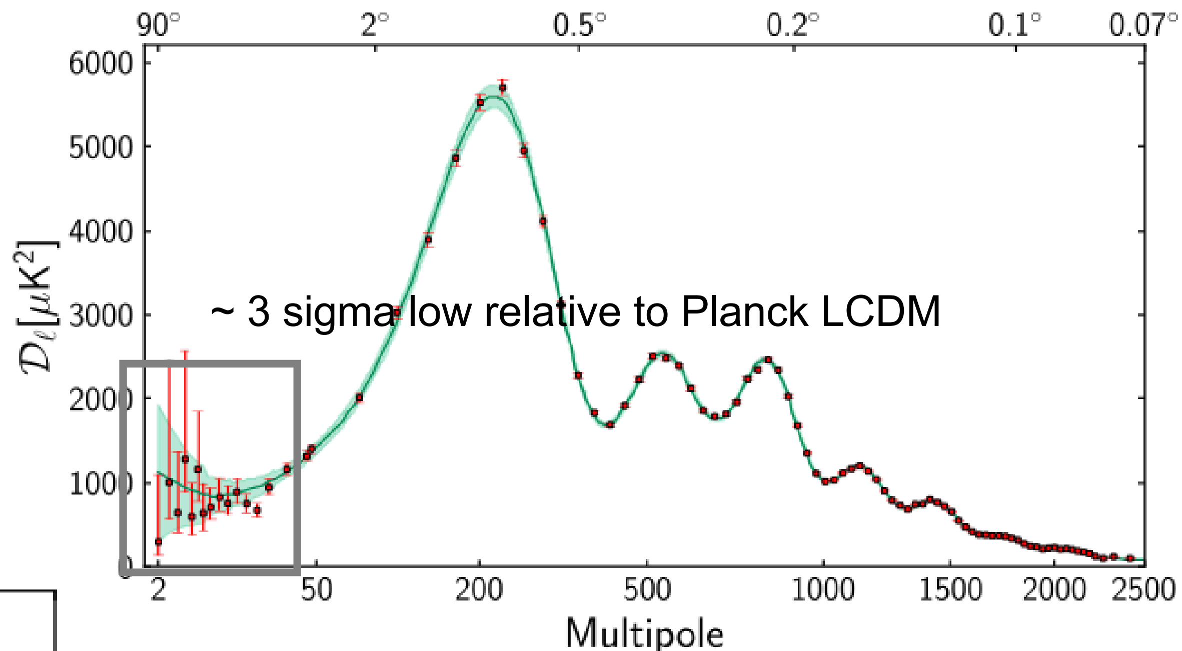
Stacking on cold spots

Stacking on random spots

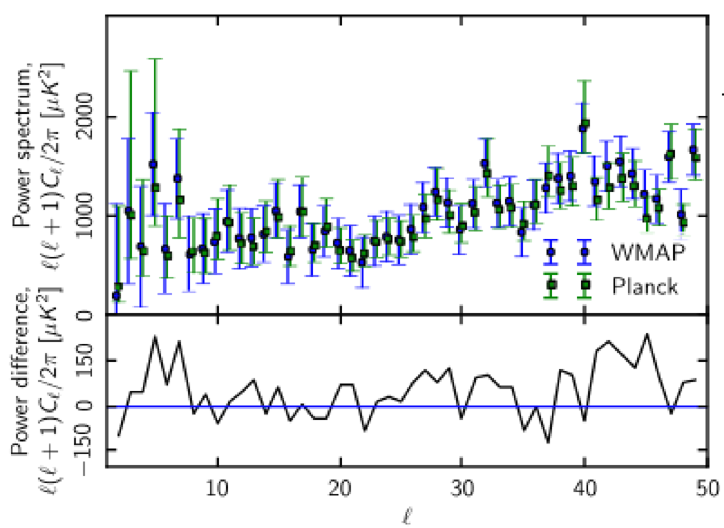
The deflection angle power spectrum

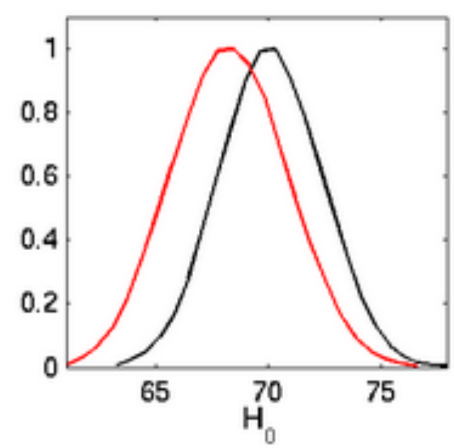


A curiosity: Low-L tension with LCDM



Planck and WMAP in the
2<L<50 region





WMAP
WMAP+(no L<30 TT)

Conclusions

- Planck has performed beautifully
- The ΛCDM model provides a very good fit to the Planck data, except possibly on the largest scales.
- The Planck-calibrated LCDM predictions for BAO observables agree perfectly with the data, while the predictions for H_0 disagree with the most precise, more direct methods.
- The CMB damping tail has no preference for extra neutrino species.
- CMB lensing is playing an important role in cosmological constraints, particularly on the sum of neutrino masses.
- Combined with BAO $\sum m_\nu < 0.23\,\mathrm{eV}$ (95%; *Planck*+WP+highL+BAO).